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AN INNOVATIVE METHOD TO SOLVE THE MAINTENANCE TASK ALLOCATION & PACKING PROBLEM

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AN INNOVATIVE METHOD TO SOLVE THE MAINTENANCE TASK ALLOCATION & PACKING PROBLEM

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"If I have seen farther than others,
it is because I stood on the shoulders of giants."
— Sir Isaac Newton

Resumo

Este estudo apresenta um método inovativo para resolver com eficiência o problema de alocação e empacotamento de tarefas de manutenção (TAP), contribuindo para o setor de aviação que recentemente fez grandes progressos em direção a um futuro sustentável. A integração dos princípios da indústria 4.0 com a utilização de materiais aeronáuticos mais sustentáveis e a implementação de novas tecnologias no projeto de sistemas, incluindo novos sistemas de propulsão, resultaram no desenvolvimento de aeronaves que são ao mesmo tempo mais eficientes e sustentáveis. Em relação aos aspectos de manutenção, a utilização de tecnologias disruptivas e a implementação das funcionalidades da manutenção digital permitem a análise de dados em tempo real, facilitando o monitoramento e predição da saúde do sistema, aumentando a eficácia da manutenção baseada em condições. Apesar dos avanços, a indústria aeronáutica continua a enfrentar desafios na área de suportabilidade. A manutenção é considerada um dos fatores estratégicos que contribuem para a alta produtividade e suportabilidade de um sistema complexo, sendo importante para garantir que o sistema seja capaz de operar com segurança e alto desempenho operacional ao menor custo possível. Ao planejar a manutenção se faz necessário garantir que a estratégia adotada atenda a esses objetivos. O método proposto visa resolver parte dos problemas encontrados no processo de desenvolvimento de planos de manutenção, onde a indústria perde uma parte do potencial de otimização ao desenvolver as estratégias de manutenção sem o suporte de modelos e ferramentas científicas. A abordagem leva em consideração, os limites de voo dos componentes, probabilidade de falhas, custos de manutenção preventiva e corretiva, custo de oportunidade devido à indisponibilidade da aeronave, economia devido à alocação inteligente de tarefas preparatórias, e o sequenciamento de execução das tarefas, com base no relacionamento entre as tarefas e limitações de recursos. O problema foi resolvido em 2 fases: primeiro, aloca-se tarefas aos pacotes de forma otimizada (minimizando o custo geral sem ultrapassar os limites de segurança) e então, para cada pacote de trabalho, agrupa-se as tarefas como um problema de empacotamento, organizando tarefas multidimensionais em caixas multidimensionais, de forma a minimizar o tempo de inatividade da aeronave. O modelo criado mudou a forma de como as tarefas são alocadas. O método de resolução do problema foi validado em várias instâncias de testes utilizando dados gerados sinteticamente a partir de informações estatísticas e registros reais de manutenção de componentes aeronáuticos. O método de modelagem e resolução do problema apresentou resultados excelentes no âmbito deste estudo. Obteve-se, uma melhor alocação e sequenciamento das tarefas, o que resultou em maiores taxas de disponibilidade e diminuição substancial dos custos totais de manutenção. Em termos de consciência situacional, o modelo proposto proporciona ao planejador a flexibilidade necessária para gerir melhor as restrições de recursos e, ao mesmo tempo, alcançar resultados ótimos.

Abstract

This study introduces an a cutting-edge method for efficiently resolving the aircraft maintenance task allocation and packing (TAP) problem, therefore making a valuable contribution to the aviation sector. The anticipation of increasing industry demand and competitiveness among manufacturers and operators increases the requirement for consistent technical progress in aircraft efficiency and supportability. Recently, the aviation sector has made great progress toward a sustainable future. The integration of industry 4.0 principles, utilization of enhanced materials, and new systems technologies has resulted in the development of aircraft designs that are both more efficient and sustainable. In terms of maintenance, the use of digital technology and the implementation of e-maintenance features enable the analysis of data in real-time, facilitating the monitoring and prediction of system health. This enhances the efficacy of condition-based maintenance and enables the use of predictive and prescriptive maintenance approaches. Nevertheless, despite advancements in aircraft design and maintenance, the industry continues to face challenges in the form of suboptimal pportability. Maintenance is considered one of the strategic factors that contribute to the high productivity and supportability of a complex system, being important to ensure that a complex system is able to operate safely, with high operational performance at the lowest possible cost throughout its life cycle. When planning maintenance for complex systems it is needed to assure that the maintenance strategy complies with these goals. The problem is gaps found in the process of developing maintenance plans, where the industry misses a part of the optimization potential while developing the maintenance strategies. The proposed method for efficiently resolving the aircraft maintenance *TAP* problem takes into accounts factors such as due flight time of components, failure probability, preventive and corrective maintenance costs, opportunity cost due aircraft unavailability, savings due to smart allocation of preparations, and opportunities for the recurrence of tasks, based on available number of mechanics, and a limited number of people in each aircraft zone and task relationship. The TAP is resolved it in 2 phases: first the model optimally allocates tasks to packages (guaranteeing that the component will fly within its safety flight hour range and the overall cost is minimized); and then, for each work package, it groupstasks as a *Bin Packing Problem* by arranging multidimensional tasks into multidimensional bins, attempting to minimize downtime.

This method changed the way tasks are better allocated to packages by packing them into time bins, thus introducing the Task Allocation & Packing Problem (TAPP), which is the target of this work. The method created to solve the TAPP is named *ETAPPS* (Efficient TAPP Solver). ETAPPS was validated by employing maintenance records data of aeronautical components that were synthetically generated using statistical data from real maintenance records. The modeling and solution procedure provide very excellent results within the scope of the research by enhancing the overall arrangement of the tasks, resulting in higher availability rates and a substantial decrease in total maintenance costs. In terms of situational awareness, it provides the user with the flexibility to better manage resource constraints while still achieving optimal results.

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List of Abbreviations and Acronyms

AC	Advisory Circular
AGAN	As Good As New"
AIAA	American Institute of Aeronautics and Astronautics
ALS	Airworthiness Limitation Section
ASK	Available Seat Kilometers
ASM	Available Seat Miles
ATA	Air Transport Association
CM	Corrective Maintenance
CMCF	Corrective Maintenance Cost Factor
CMR	Certification Maintenace Requirement
CMTF	Corrective maintenance time factor
CPCP	Corrosion Prevention and Control Program
CRF	Cost Rate Function
EC	Engine Cycle
DMC	Direct Maintenance Costs
DT	Downtime
EH	Engine Hour
ETAPPS	Efficient Task Allocation and Packing Problem Solver
EZAP	Enhanced Zonal Analysis Procedure
FAR	Federal Aviation Regulations
FC	Flight Cycles
FEC	Failure Effect Category
FFD	First-Fit Decreasing
FH	Flight Hours
FMEA	Failure Mode and Effect Analysis
FSL	Fuel System Limitation
FTA	Fault Tree Analysis
GDP	Gross Domestic Product
HALT	Highly accelerated life test
HASS	Highly Accelerated Stress Screening

HOC	Hourly Opportunity Cost
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IPS	Integrated Product Support
IVHM	Integrated Vehicle Health Management
LD	Landings
L/HIRF	Lightning and High-Intensity Radiate Fields
LLP	Life Limited Part
MFDT	Mean Fractional Dead Time
MHC	Labor Cost
MIP	Mixed Integer Pogramming
MMEL	Master Minimum Equipment List
MO	Months
MPD	Maintenance Planning Data
MRB	Maintenance Review Board
MSG	Maintenance Steering Group
MSI	Maintenance Significant Item
MTB	Maintenance Type Board
OAMP	Operator Approved Maintenance Plan
OCD	Daily Opportunity Cost
OEM	Original Equipment Manufacturer
OHD	Daily Operational Hour
PHM	Prognostic Health Monitoring
PM	Preventive Maintenance
RASK	Revenue per Available Seat Kilometers
RASM	Revenue per Available Seat Miles
ROI	Return of Investment
RPK	Revenue Passenger Kilometers
SSI	Structural Significant Item
TAP	Task Allocation Problem
TAPP	Task Allocation and Packing Problem
TC	Type Certification

List of Symbols

A	availability
$\|A_j\|$	set of preparation task needed for task t_j
$area_x$	zone area
$available_r$	available mechanics for each technical qualification
$\|B^i\|$	set of maintenance bins
$\|C\|$	set of components
cid_j	component identifier related to j-nth task
cmc_j	cost associate to corrective maintenance on j-nth task
$cmdt_j$	CM downtime associated to j-nth task
$cmoc_j$	CM opportunity cost associated to $cmdt_j$
dt_b^i	downtime to execute tasks on bin b^i
id_x	zone z_x identifier
λ_t	failure rate of the t-nth component
$last_j$	hours of last execution of j-nth task
lim_j	the flight time limit to accomplished j-nth task
$limit_x$	the maximum number of people to remain simultaneously in the zone z_x
$\|M\|$	set of maintenance technicians.
$major_x$	1 if the zone is Major, 0 otherwise
mat_j	material cost of maintenance of j-nth task
mh_j	labor hour for preventive maintenance of j-nth task
$\|MR\|$	set of maintenance records
$name_t$	a defining name for component of t-nth component
$nmec_j^r$	(number of mechanics of qualification (m_r) needed)
$\|P\|$	set of maintenance preparations
$\|P_i\|$	set of preparations used in the package s_i
pmc_j	PM cost of j-nth task
$pmdt_j$	PM downtime of j-nth task
$pmoc_j$	PM opportunity cost associated to to $pmdt_j$
$preps_j$	(list of preparations necessary to be accomplished prior or after task t_j)
$qualif_j$	(mechanic qualification needed)

$qualif_r$	technical qualification
$\lvert S \rvert$	set of maintenance packages
$\lvert T \rvert$	set of maintenance tasks
$usage_t$	the usage parameter of t-nth component
$wage_r$	wage for each qualification ($qualif_r$) expressed in US$/h
$Weibull\ \eta_t$	the Weibull characteristic life of t-nth component
$Weibull\ \beta_t$	the Weibull shape parameter of t-nth component
$\lvert Z \rvert$	set of aircraft zones
$znum_j^{xr}$	(number of mechanics with skill m_r needed for task t_j in zone z_x)
$zone_j$	(aircraft zones where the task will be executed)
$ztime_j^{xr}$	(time required for each qualification m_r needed for task t_j to be executed in zone z_x)

Contents

1 Introduction

1.1 Background

The expectation of expanding industry demand and competitiveness among producers and also among operators drives the need for continuous technological advancement aimed at more efficient aircraft and supportability. The aviation industry has made significant strides in recent years and continues to work toward a sustainable future. In terms of product, the incorporation of industry 4.0 concepts, use of improved materials such as carbon fiber composites, titanium alloys, and 3D-printed structures, adoption of advanced propulsion systems such as more efficient turbo fan, hybrid and electrical engines, along with advancements in aerodynamics which reduce drag and improve fuel efficiency, have led to the development of more efficient and sustainable aircraft designs (SONG; LIU, 2022; YUSAF *et al.*, 2022).

On the maintenance side, the digital technology and use of e-maintenance features permit real-time data analysis and ability to monitor and predict the health of systems. It improves condition-based maintenance effectiveness, and allows for the implementation of predictive and prescriptive maintenance strategies.

Nevertheless, despite advancements in aircraft design and maintenance, the industry continues to face challenges in the form of inefficient aircraft supportability. This inefficiency not only leads to higher operating costs, but also affects the aircraft's dependability and availability (ABRAHÃO *et al.*, 2019).

Attempting to solve the problem of inefficient aircraft supportability, researchers are exploring process and innovative approaches to improve logistics and maintenance performance. As regarding the Integrated Product Support (IPS) development process, Abrahão *et al.* (2019) build-up the AeroLogLab tool® to help the integration of IPS activities since the early phases of the complex system development to assure a better maturity of product supportability at the entry-to service phase. Other initiatives investigate the use of disruptive technologies, such as the integration of artificial intelligence and machine learning techniques with predictive maintenance improving the accuracy of estimating remaining useful life. Also, the development of smart technologies has made it possible to switch from planning maintenance based on past experience and assumptions to using smart sensors, machine learning, and big data analytics. These new technological possibilities allow for the prediction of previously difficult-to-predict events (OCHELLA *et al.*, 2022; SALONEN; GOPALAKRISHNAN, 2020; KARAOGLU *et al.*, 2023). Following similar approach, the study of Dangut *et al.* (2022), explore the aircraft maintenance logs to predict failures using deep reinforcement learning techniques.

All those research efforts are justified by the important role that aviation plays for world integration and for the global economy. As mentioned by ICAO ACI and IATA (2019), the civil aviation industry in 2019 was responsible for supporting 65.5 million jobs in the world and handling an amount of 2.7 trillion dollars, equivalent to approximately 3.6 percent of world gross domestic product (*GDP*). This value is equivalent to the GDP of Switzerland or Argentina (JAMES, 2020). On the other hand, for several years the return on investment (ROI) earned by the airlines has been below expectations and yet the profit margins are also small when compared to other industries as shown in the chart 22 of the Global Outlook for Air Transport (IATA, 2023). The aviation scenario is sometimes hostile, as occurred in the years 2008 and 2020, due to the crises that ensued. In this regard, it is highlighted the important role of maintenance since it is one of the factors that can be influenced by the manufacturer during the development of the aircraft. The preventive maintenance contributes to satisfy the airworthiness and operational demands requirements. Nevertheless, according to PeriyarSelvam *et al.* (2013) it involves costs that can range from 9 to 16 percent of an airline's total costs

This shows the importance of the research on maintenance optimization for the aeronautical industry. It can be approached from different angles, including the optimization of preventive maintenance definition, the use of predictive maintenance techniques, and the implementation of maintenance-friendly design principles. These approaches aim to balance the trade-off between the cost of maintenance and the availability of the aircraft, ensuring that aircraft systems are maintained in a cost-effective and reliable manner.

In summary, by leveraging the latest technological advancements and innovative research approaches, the industry can enhance the supportability of aircraft and improve the reliability and availability of aircraft systems.

1.2 Motivation

Maintenance is regarded as one of the strategic factors that contribute to the high productivity of a complex system, and it is necessary to ensure its safe operation and operational capacity at the lowest possible cost throughout its life cycle. Complex systems (i.e., systems comprised of parts with distinct operating characteristics) can be utilized economically and safely if the proper maintenance strategies are employed (MLYNARSKI *et al.*, 2019).

Complex systems must therefore perform planned preventive maintenance (PM) to avoid unexpected failures, restore inherent functionality, and maximize their service life. The maintenance of complex systems can be considered a decision-making problem with several attributes, including safety, downtime, logistics delays, and costs, among others.

In the aeronautical industry, safety, operational performance, and cost objectives are directly affected by the preventive maintenance strategies established during product development. The resulting maintenance plan is presented in the Maintenance Planning Data (*MPD*) publication and includes, among other information, the frequency of scheduled maintenance tasks that need to be adequately defined, in order for the product to meet the performance expectations of the users at the lowest possible operating and maintenance cost.

One of the main stakeholders in the aviation industry is the airline operators that provide the service to the end users. Before beginning effective operation of their aircraft, operators must develop their own preventive maintenance plans to be approved by their authorities and support their operation and maintenance. These plans are based on the manufacturer's instructions for continued airworthiness provided by manufacturer in the maintenance data set.

The manufacturer`s MPD is the main source of information to assist operators in developing the initial maintenance plan. The tasks are distributed along several sections of the MPD organized by systems according to the ATA standard, and with their maximum intervals. In some cases, Original Equipment Manufactures (*OEM*) provide a suggested task packaging in one of the MPD annex. Even though these suggestions are based only on general utilization profiles and task intervals.

It is desirable that the organization of tasks into packages be optimized in a way to consider all the relevant aspects of operation and maintenance resources to minimize the total maintenance costs, maximizes fleet availability, and facilitates flight and maintenance planning. The resulting plan needs to be organized and flexible in order to allow proper management and task sequencing without increasing administrative workload.

An effective Preventive Maintenance, scheduled or prognosis based, avoids failures that need costly corrective maintenance and would cause flight cancellations or delays, affecting the airline network`s schedule and profitability (SMITH; HINCHCLIFFE, 2003). Aside from the production loss caused by maintenance downtime, according to Peterson *et al.* (2013), these events have an impact on the airline's expenses due to additional costs associated with crew, fuel, aircraft, and maintenance. The cost of a commercial aircraft out of operation is around 70,000.00 USD per day as noted by Senturk and Ozkol (2018).

The maintenance, fuel, and oil consumption constitute the predominant portion of the overall operational expenses. The manufacturer can employ design strategies to enhance the consumption ratio, however, it has limited influence over fuel pricing. On the other hand, considering the reliability, and maintainability factors, as well as, the precision in determining the frequency of maintenance tasks during the development of a product can greatly save maintenance costs during its life cycle. System availability and maintenance expenses are influenced by the time between maintenance cycles, the quantity of resources, and the duration of each maintenance activity.

In summary, an inefficient preventive maintenance program, produced by inaccurate Method can affect the stakeholders in terms of:

- Operational availability and costs
- Disruption of the flight network
- Investment Return
- Future sales and the reputation of the aircraft market

Hence, doing research in the field of maintenance optimization holds significant importance for the industry as it aids in addressing the persisting supportability challenges faced during the development process. Consequently, this contributes to enhancing the product's performance and mitigating the negative impacts that operators encounter during flight and maintenance planning.

1.3 Research Problem

The problem is the gaps found in the process of developing maintenance plans, such as the absence of an efficient model and tools, which present sub optimalities or inconsistencies to obtain the best cost-benefit ratio. Inefficient or incomplete methods may lead to sub-optimal and, perhaps, too conservative definitions of maintenance tasks and intervals.

The statement of problem above is based on the review of literature and experience gained in the application of the MSG-3 methodology to build maintenance requirements for a variety of commercial, executive, and defense aircraft. Liu *et al.* (2006) and Lv *et al.* (2017) concur that the main problem is the lack of a systematic and continuous approach to consider all the important parameters during the development and operation of maintenance plans.

It is observed that there are several opportunity points to be improved in the methodologies used to define maintenance requirements and intervals, and in the maintenance plan elaboration. The study of Ahmadi *et al.* (2010) lists some potential areas that could be improved in the current MSG-3 framework, ranging from the initial failure mode and effect analysis (FMEA) up to the task interval selection criteria. The authors mention that despite the comprehensiveness and consistency of the MSG-3 methodology used worldwide in the development of initial maintenance programs, the definition of task intervals is mostly based on analysts` experiences.

Also, the task interval definition during the Maintenance development is pointed out by Liu *et al.* (2006) as a process that relies mainly on engineering experience in a similar application. These difficulties for defining the task interval is also highlighted in the MSG-3 document (AIRLINES FOR AMERICA, 2015), where it is assumed that the initial intervals should be based on the available data and "good engineering judgment", which denotes a certain degree of inaccuracy.

The systematic failure to apply clear scientific criteria and methods to define maintenance intervals during the development of initial aircraft maintenance requirements and plan results in the definition of maintenance based solely on the analysts' experience and qualitative judgment, which are quite conservative and potentially inaccurate. The impact is attributable to difficulties in ensuring the availability and readiness metrics of aircraft fleets, as well as the ensuing rise in their respective life cycle costs.

In addition, in the beginning of the development of a new system, typically not all of the information required for the correct definition of the initial maintenance intervals is available with adequate maturity. There is an expected growth in reliability and maintainability data during the development. In the absence of a process and tool to continuously monitor these parameters during development, a conservative maintenance plan is defined and reviewed only after extended periods of operation. The same concern applies to the monitoring and evaluation of field data to identify proactively the need to evolve the original maintenance plan.

The outcomes of some effort to evaluate and revise the initial maintenance plan demonstrate the significance of developing an effective maintenance plan during the development phases. Original Equipment Manufacturers (*OEM*) usually establish a program to evolve the maintenance plan only after ten or more years of operation. In order to adjust their aircraft maintenance plans, OEMs must evaluate field data and follow a guideline similar to that presented by Goncalves and Trabasso (2018).

Typically, these efforts benefit airlines by lowering costs and downtime. For example, according to Mcelroy (2006), during the development of the B737NG aircraft, Boeing saved 2,586 hours per aircraft, resulting in 40 days more availability and a total savings of USD 25,046,400 for an airline with 20 airplanes. This study assumes that a portion of this gain can be obtained from the start of the product operation phase with the use of an optimization model that can adapt to changes in input parameters, bringing resilience to the system.

The concept of resilience in this context is the ability to recognize the deterioration of key parameters that may impact the effectiveness of support services. By employing an agile and methodical approach,it may be possible to find optimal solutions to ensure the continued operation in a manner that is both safe and economically viable.

In summary, the resulting maintenance planning (PM) is conservative due to limitations faced by maintenance engineers, such as the absence of an efficient tool to complement the MSG-3 analysis and support the allocation of tasks during the design of the operatorś maintenance plan which may result in inefficient maintenance plans, i.e., more costly than they could be and with availability rates lower than what is possible to be achieved. Also, the absence of a resilient system to monitor the supportability field performance implies in losses for several years.

The challenge is how to define a maintenance plan that is optimal, or very close to optimal. It is desirable that task allocation considers all relevant parameters for the best possible cost-effectiveness of support during the all the life-cycle.

1.3.1 Context of the Problem

The initial maintenance requirements for a new aircraft are derived from the type certification (TC) process and the Maintenance Review Board (MRB) or Maintenance Type Board (MTB) process as shown in the Figure 1.1. The requirements originated by the certification (TC) process aim to keep the inherent safety level defined in the type design during all operational life, and includes limits for systems and structures items.

Parallel to the certification, the Maintenance Review Board (MRB) or the Maintenance Type Board (MTB) provides the process and rules for developing the initial minimum maintenance requirements to assure the continued airworthiness of aircraft. Besides safety, the MRB process evaluates the operational and cost consequences of failures. The aeronautical industry's scheduled maintenance program development baselines are the advisory circular 121-22 (C) (UNITED STATES, 2012) and the MSG-3 methodology (AIRLINES FOR AMERICA, 2015).

The resulting requirements are presented in the MPD publication and includes, among other planning information, the frequency of scheduled maintenance tasks required for the aircraft to meet both the performance expectations of the users and airworthiness requirements.

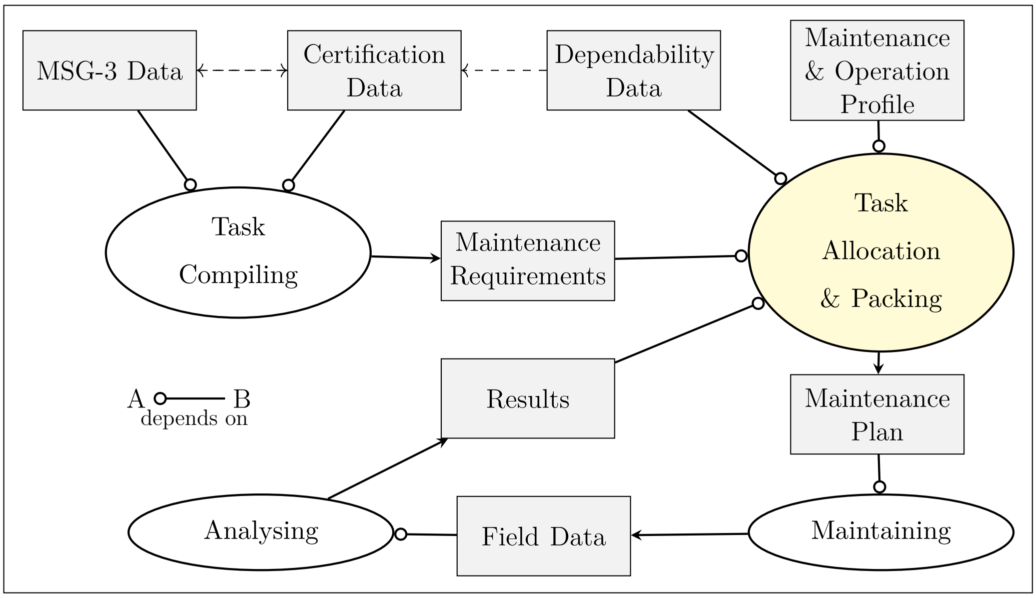

FIGURE 1.1 – Maintenance Plan Development

Processes and the MSG-3 methodology used to define the initial maintenance plan are constantly evolving, and significant improvements, such as modifications to the pre-packaging concept and the recent introduction of the possibility of using health monitoring systems, effectively contribute to enhance the definition and implementation of the operator's maintenance plan.

This research focuses on the problem of task allocation in packages (Task Allocation and Packing) process in Figure 1.1, that occurs after the definition of maintenance requirements by the certification and MRB/MTB activities. The objective of the task allocation and packing process is to produce the final maintenance plan, which serves as a reference point for the operator to approve its own maintenance plan necessary for the maintenance of its aircraft fleet.

The elaboration of maintenance plan for the execution of maintenance tasks in aircraft is a major concern of the Production Planning and Control, Maintenance and Engineering and Operations sectors of the airline companies. A maintenance plan consists of the assignment of maintenance tasks to a predefined packages (and eventually keep them as out-of-phase tasks) within a time horizon, commonly known as a task allocation problem (TAP). It is a combinatorial issue that maintenance operators must solve on a daily basis, based on OEM-specific maintenance planning instructions.

There are several options to consider when creating a maintenance plan. The following discussion presents two extreme alternatives to contextualize the difficulties encountered in developing a maintenance plan.

An alternative would be to attempt to utilize the time restriction for the secure functioning of every aircraft component. In this scenario, the maintenance plan would emphasize the optimal and secure utilization of every component and system, therefore preventing any loss of operational hours. Nevertheless, the maintenance plan must establish an individual control for each item and its respective preventive maintenance tasks. Because failures are probabilistic in nature, there is a higher likelihood of experiencing failures at inconvenient times. This can lead to increased unavailability and the accompanying expenses.

Another option would be to attempt to combine multiple maintenance tasks into packages, despite the potential loss of flight hours for some components. This alternative, known as packing, generates less substantial working packages but necessitates a relatively longer aircraft downtime. It may be able to anticipate the execution of items *out of phase*[1] (OOP - Out of Phase, not included in the maintenance package) and safety controlled items (items that require specific attention to its life limit). However, it allows for improved planning of activities and resources, as well as a reduced risk of additional pauses for modifications resulting from Service Bulletins and Airworthiness Directives, as well as for repairs. Regarding quality, there is an extended period for correcting deferred failures enhancing the aspects related to human factors.

The definition of the best maintenance task allocation strategy is directly linked to the operator's concept of maintenance, location and availability of resources, and demands from the operation sector that controls the flight network. The challenge of the maintenance sector is to meet all the demand of the operation sector with aircraft in airworthy conditions.

The best possible Maintenance Plan (PM) is the one that meets the maintenance objectives with an optimal cost-benefit ratio via an adequate combination of the different portions of costs and gains due to the packaging and sequencing of tasks.

As mentioned, the absence of a scientific method to support the task allocation and packing process, that in practice is based only in the experience of maintenance plan engineers leads to inefficiencies. Task intervals, material, man-hour and access from preventive maintenance are normally considered in the packaging process. However, the packaging is not optimized and excludes costs of corrective actions based on the likelihood of item failures, cost production losses, and savings from packaging tasks that share the same preparation tasks.

Investigating the possibility of including those parcels of costs and savings, and integration with proactive data monitoring, during the aircraft development and operation stages, is thus an important strategy to consider. It is important to mention that the

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[1] There are tasks that, by their nature and origin, should be considered OoP and can even be unpacked. Items that are not controlled by the hours/cycles or months of the aircraft but by their lifetime or use, i.e., items controlled by the hour or engine cycle, APU, some equipment that follows requirements established in its certification (fire extinguishing bottles, oxygen bottles, ELT batteries, etc.)

latter parameters are not correctly addressed in any of the previous phases of the task interval definition.

In conclusion, it is necessary to develop methodologies and tools to improve the assignment of tasks in packages and determine the most suitable sequence for executing tasks within each package during maintenance stoppages. This is done with the goal of optimizing maintenance costs and availability, and ensuring the continuous airworthiness of the aircraft.

1.4 Objective

The objective of this study is to develop and evaluate a model that improves the precision of task allocation in packages and generates optimal maintenance plans. This model takes into account all costs parcels, packaging savings, failure probability, and available resources. The goal is to establish an optimal system availability-cost relationship while ensuring safety and meeting stakeholder needs to the greatest extent possible.

1.4.1 Specific Objectives

The specific objectives of this research are to:

1. identify and verify potential areas for improvement in the development and adjustment of the scheduled maintenance program.
2. An analysis of the Task Allocation Problem (TAP) within the framework of pertinent academic research and practical applications in the industry.
3. Explore optimization techniques and methodologies that can be employed to assist in problem-solving.
4. Identification of the critical parameters that must be employed when packaging.
5. Identification of parameters considered in the sequencing of task execution.
6. Assess the potential enhancements that the disruptive technology could bring to the original allocation of tasks and its future modifications.
7. propose an appropriate methodology and model for selecting of the most effective maintenance plan strategy.

1.5 Research Questions

To achieve the above aims, the following research questions have been formulated:

- What are the specific areas that offer opportunities for enhancement when examining the challenges encountered by analysts and operators when applying the MSG-3 methodology and producing the final maintenance plan?
- How can the reliability and maintainability parameters of the aircraft system be taken into account?
- What optimization tools and methodologies are utilized in tackling the problem?
- How to identify and select the most effective package to allocate a maintenance requirement originated by the MSG-3?
- What are the essential elements for establishing the optimal maintenance plan for the customer?
- How can new technologies be utilized to enhance the process of developing and updating maintenance plans?

1.6 Research Scope and Limitations

This study specifically examines the task allocation process of the maintenance definition framework that takes place during the development phase of the product, as shown in Figure 1.1. This process significantly affects the operators' maintenance planning over the whole lifespan of the aircraft. The system takes into account the civil aviation certification standards and recommendations, ensuring that each item adheres to the maximum interval limit set by either the MSG-3 or certification analysis. These limits came in function of the failure consequences on aircraft operation or component technical behavior. The model incorporates the maximum allowable interval as a restriction to determine the optimal arrangement of item tasks within the established maintenance packages. Additionally, the study takes into account another significant issue, from the perspective of an operator, which is the arrangement of task sequencing within each package.

Additionally, this study conducts an initial assessment of how the maintenance program can be modified depending on the product development reliability growth program or in-service data collected during operation phase, with the goal of creating a resilient maintenance plan. The present research work does not include the complete dynamic updating of maintenance plan and integration of flight and maintenance planning due to time constraints.

For the resolution method it was tested both exact and heuristics methods and based on the results it is used the *Branch-and-Cut* method provided in the Python Mixed Integer Problem (MIP) solver. For task sequencing is implemented using the First-Fit Decreasing(FFD) Heuristic. The resolution method was validated by utilizing a sample of aeronautical items, synthetically generated and based on statistical data from real commercial aircraft maintenance records and in general considers the following assumptions:

- Items can show a increasing or a constant failure rate characteristics;
- Items are subject to perfect maintenance and are considered as good as new (AGAN) after restoration maintenance activities;
- No variability in the labor allocated for each task.
- Labor of preventive maintenance based on data of similar task performed on commercial aircraft;
- Labor of corrective maintenance assumed to be three times of preventive one;
- The opportunity cost related to the revenue lost during the period when the aircraft is grounded for maintenance.
- Savings for packaging tasks based on the similarity between tasks as regarding the access and general tasks required to perform the tasks.

1.6.1 Research Contribution

Significant academic contributions of this work is the development of an innovative optimization framework to solve the task allocation problem (TAP), that considers all essential parameters, allowing complex systems to remain effective throughout their respective life cycles. The development encompasses the investigation of important factors that influence the supportability performance of a complex system, research on optimization and modeling tools.

For the industry, this work contributes with a framework able to develop optimized maintenance plans, contributing to improve the maturity and effectiveness of product supportability since the start of operation. In the operation phase, it can assist operators in their short and medium-term maintenance planning and activities sequencing. The expectation is that this proposal will ensure a better maturity of the logistical support elements that are affected by the maintenance at the beginning of the operation phase, thus avoiding losses that are normally discovered and corrected only after years of operation. This research also introduces the concepts of field and operation data learning that can be used to develop a method to proactively identify opportunities to evolve the maintenance plan according to the field maintenance and operation data.

1.7 Methodology Summary

This topic provides an overview of the research methodology used to collect and analyze data in order to achieve the specific and general objectives.

A combined exploratory, descriptive, and explanatory approach was chosen to attend the objectives of this study.

The problem description employed an exploratory methodology, which involved observing various scenarios and examining the significance of supportability challenges to the aerospace industry.

The research project considered the experiences and evaluation of industry needs, as well as identified gaps found throughout the literature review. Consequently, the objectives, hypothesis, and test procedures are established.

A deductive analysis was conducted to establish the theoretical framework, develop the conceptual model, determine the optimization parameters, and define the objective function.

The resolution method was defined using both exploratory and deductive approaches. Initial data were acquired and verified. Quantitative and deductive approaches were employed to apply and validate the model with the supervisor and pairings.

The final tests were conducted using artificial data generated from real commercial maintenance data. Quantitative and exploratory methods were utilized to evaluate results, test the hypothesis, and emphasize accomplishments and potential future endeavors.

1.8 Organization

This work is organized by chapters with the following contents: Chapter 1 contains the introduction to the research subject, describing the context, objective, motivation and scope of the study. It also summarizes the methodology and contributions of the research. The Chapter 2 provides a theoretical description of key maintenance subjects, and a literature review of studies related to maintenance optimization and task allocation on packages. The research methodology is described in the Chapter 3. It presents the steps followed to develop and test the proposed model. The Chapter 4 presents test results, observations and discussion of the main points found on research tests. In the Chapter

5 is presented the study conclusions and achievements, as well as, possible avenues for future research.

2 Literature Review

2.1 Introduction

The preceding Chapter provides an overview of the problem, its context, and the objectives of the research. This Chapter highlights the main findings of prior studies on maintenance optimization and identifies the gaps and limitations of the existing research that this study aims to tackle. Furthermore, it provides a comprehensive summary of the fundamental principles that support the research problem.

2.2 Theoretical Framework

This Section provides an overview of the key theories and concepts that are pertinent to the study.

2.2.1 Scheduled Maintenance Development

Maintenance is the process of ensuring that a system continually performs its intended function at its designed-in level of reliability and safety (KINNISON, 2004). It includes all actions necessary for retaining a system or product in, or restoring it to, a desired operational state (BLANCHARD, 2004). Márquez (2007) resumes that the retention and restoration are denominations that can lead to two main types of maintenance: preventive and unscheduled corrective. The diagram presented in Figure 2.1 showcases the function of preventive maintenance plans, which are designed to ensure that the system does not fall below the required level of reliability. This situation is categorized as a functional failure condition that requires a unscheduled corrective action.

In certain system design, the level of dependability is determined based on the user's system needs, rather than being determined by the system's actual capabilities. Moubray (2001) asserts that preventive maintenance should be implemented with the aim of ensuring the minimal requirements necessary to guarantee the acceptable degree of depend-

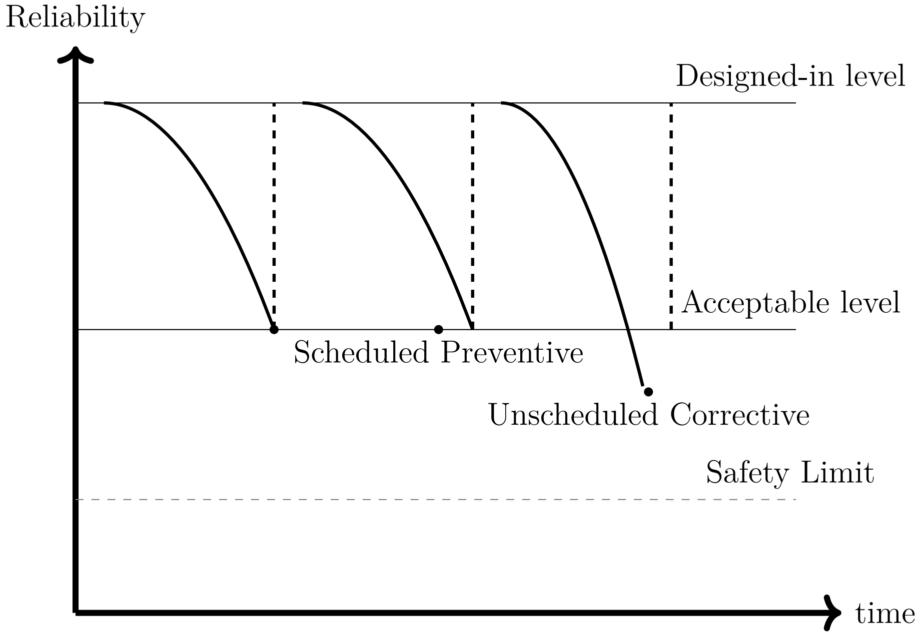


FIGURE 2.1 – Scheduled and Unscheduled Maintenance (Adapted from KINNISON, 2004)

ability of a system. So, the purpose of maintenance is to ensure that the system operates at a level of performance that is deemed acceptable.

In the aircraft industry, the reliability level at which systems are designed is determined with a sufficient margin from safety limitations. This is done to ensure that an aircraft can continue to fly, for a specific period of time, even in the event of a functional failure, without exceeding the necessary safety limit. The period of time during which aircraft are permitted to fly with a known failure is specified in the approved Master Minimum Equipment List (*MMEL*). Any situations that exceed the safety limitations must be promptly analyzed and, if required, the system must be redesigned to ensure compliance with the safety requirements.

The objective of preventive maintenance is to preserve the operational state of a system or product, hence mitigating the potential effects of failures through the decrease of failure probability and system degradation. The maintenance activities encompassed within this approach consist of two primary categories: planned maintenance, which is performed at predetermined intervals depending on the usage parameter, and condition-based maintenance, which is conducted based on the performance and condition of the monitored item. According to Márquez (2007), condition-based maintenance encompasses predictive maintenance, which is executed by utilizing forecasts generated from the analysis of parameter degradation.

The corrective maintenance includes the actions necessary to clear the system failures identified during the system operation or the scheduled preventive maintenance task activities. The corrective type usually is more expensive than the preventive one, considering that it is an unexpected situation that can occur at any time and may impact the normal flight operation or may require correction before the next mission. To return the aircraft to service, at least it needs failure identification and verification (based on some symptom), localization and fault isolation, disassembly to gain access to the faulty item, removal and replacement with a spare or repair in place, reassembly checkout, and condition verification. (BLANCHARD, 2004)

According to Smith (2017), as shown in Figure 2.2, preventive maintenance is a crucial factor that affects the availability of the aircraft fleet, which is essential for generating revenue for the airline. Additionally, it plays a significant role in preventing failures that could jeopardize aircraft safety and operational performance. The objective is to optimize (maximize) the Revenue, by the defining the adequate level of Preventive Maintenance (PM). Therefore, it is crucial to focus on the development of preventive maintenance (PM) to address the consequences of corrective maintenance (CM) and downtime (DT). The strategy designed for the preventive maintenance has an impact both the cost and downtime. However, it is important to establish an adequate level of maintenance in order to proactively preventing failures and the expensive corrective maintenance that would otherwise result in longer downtime and higher esxpenses.

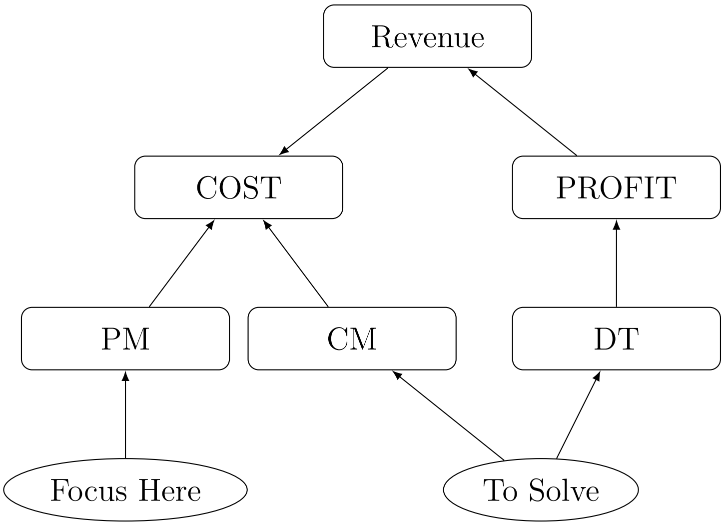


FIGURE 2.2 – Preventive Maintenance Objectives (SMITH, 2017)

In the case of commercial aviation, better performance means better profitability. On the other hand, in the defense sector, the best performance is related to readiness to carry out missions. In this sense, the maintenance of complex systems can be considered a decision-making problem with several attributes, including safety, unavailable time for system operation, logistical delays, costs, available resources, among others.

The initial maintenance program for a complex system is normally designed according to the reliability-centered maintenance (RCM) methodology, which takes into account the failure, its consequences and costs, as well as the applicability and efficacy of preventive maintenance tasks. Basson (2018) notes that RCM is a process used to determine the maintenance requirements of any physical asset in its operational context.

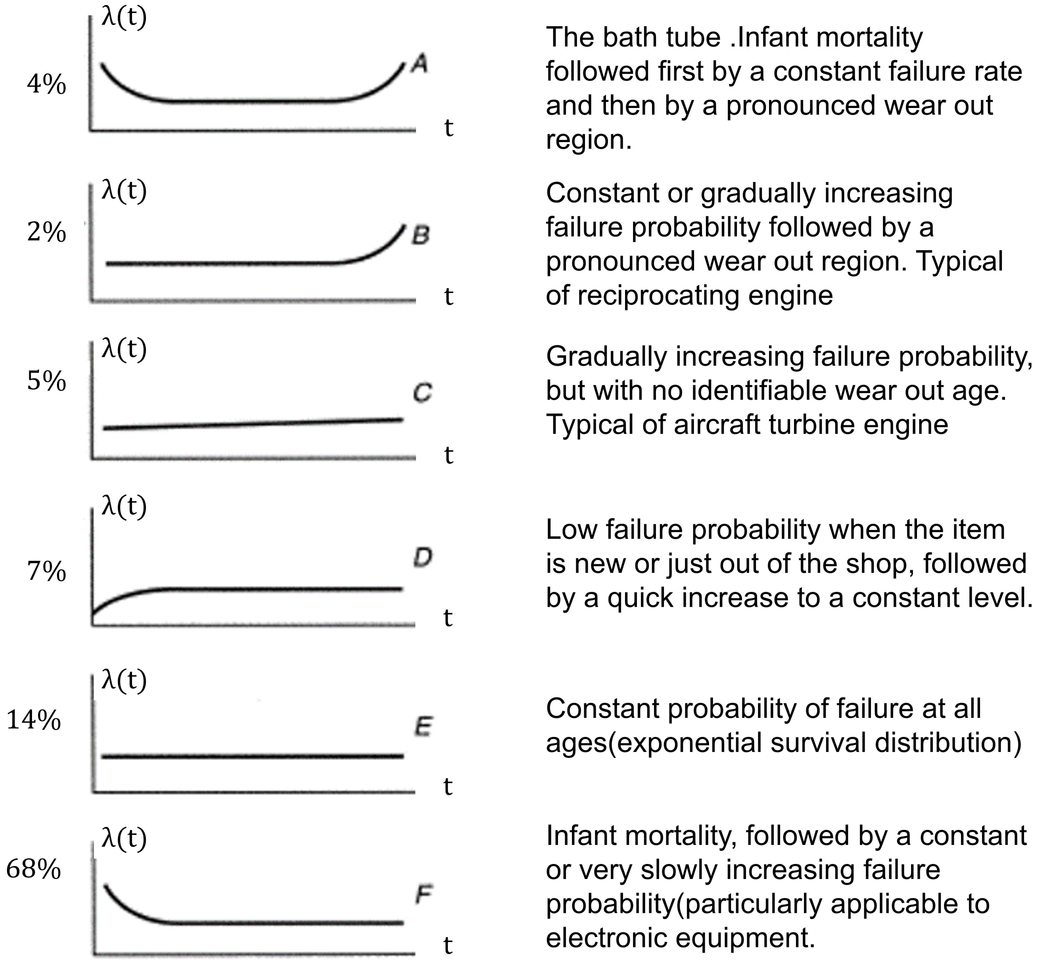
The initial steps towards establishing the foundations of the RCM were taken in the mid-1960s through a collaborative study conducted by the Federal Aviation Administration (FAA) and the American Institute of Aeronautics and Astronautics (AIAA). The FAA initiated this study due to concerns regarding engine performance, existing maintenance program efficiency, and anticipated growth in the aviation industry. The results indicate that there is no direct correlation between the frequency of overhauls and the improvement in reliability or safety, and that there is no efficient method of preventive maintenance for many components.

Using this database, United Airlines conducted a study on age-reliability trends to validate the failure patterns of the components. The findings indicated that just 4% exhibited the characteristic pattern of the bathtub curve, 11% shown signs of aging, and the majority of the components, accounting for 68%, exhibited infant-mortality followed by an unchanged failure rate throughout their lifespan, without any signs of aging.

The curves depicted in Figure 2.3 illustrates the distribution of item percentages according to each age-reliability patterns identified in the study.

A group of United Airlines engineers, namely Thomas Matteson, Bill Mentzer, Stan Nowland, and Harold Heap, responded to concerns regarding the initiation of the Boeing 747 project by going beyond the analysis of existing data. They developed a methodology that incorporated new maintenance concepts and a comprehensive review, taking into account the classification of tasks required for preserving the aircraft's essential functions. The AIAA conference in 1967 featured a presentation of a research article that unveiled the findings of the studies. This presentation led to the development of the MSG-1 methodology, which was subsequently employed in the Boeing 747 project. Shortly thereafter, the group implemented improvements to the methodology, which later became recognized as MSG-2 and was adopted by several other projects. In the early 1970s, the United Airlines group, headed by Thomas D. Matthen, held a meeting with representatives from the US Navy Office, as per the request of the US Department of Defense. The objective was to examine the research conducted by the Boeing 747 maintenance steering group (MSG-1) and assess its possible use in the Navy's P-3 and S-3 aircraft. After seven years, the US Department of Commerce published a document called "Reliability-Centered Maintenance," which drew inspiration from Nowlan and Heap's research report (SMITH; HINCHCLIFFE, 2003; BASSON, 2018).

Currently, the aeronautical industry uses the MSG-3 methodology, which is an evolution of the first edition of the MSG-1 manual and was released after the publication of the RCM report, and includes all the lessons learned by the working groups in this period.



The bath tube .Infant mortality followed first by a constant failure rate and then by a pronounced wear out region.

Constant or gradually increasing failure probability followed by a pronounced wear out region. Typical of reciprocating engine

Gradually increasing failure probability, but with no identifiable wear out age. Typical of aircraft turbine engine

Low failure probability when the item is new or just out of the shop, followed by a quick increase to a constant level.

Constant probability of failure at all ages(exponential survival distribution)

Infant mortality, followed by a constant or very slowly increasing failure probability(particularly applicable to electronic equipment.

FIGURE 2.3 – Age-reliability patterns (Adapted from SMITH; HINCHCLIFFE, 2003)

The initial maintenance requirements for a new commercial aircraft are derived from the type certification (TC) process and the Maintenance Review Board (MRB) process (UNITED STATES, 2012). The requirements originated by the certification (TC) process aim to keep the inherent safety level defined in the type design during all operational life. These requirements are considered limitations of the type design and are derived from different safety analysis:

1. Certification Maintenace Requirement based on System Safety Assesment defined by the FAR 25.1309
2. Airworthiness Limitation Section (ALS) from the Structural Damage Tolerance according to FAR 25.571
3. Fuel System Limitation (FSL) according to FAR 25.981 Fuel tank ignition prevention
4. Life Limited Part from fatigue analysis of FAR 25.571

Through the Maintenance Review Board (MRB) or Maintenance Type Board (MTB) process, manufacturers, regulatory authorities, vendors, operators, and industry together develop the initial scheduled maintenance and inspection requirements for new aircraft. The global aeronautical industry uses the MSG-3 (ATA) methodology (AIRLINES FOR AMERICA, 2015), which has undergone several revisions since its introduction in 1980, to define the scheduled maintenance requirements.

This methodology is the result of a collaborative effort by representatives of manufacturers, operators, and authorities, who have met regularly to develop it. Currently, the employed methodology is documented in MSG-3-Revision 2018.1.

The MSG-3 scheduled maintenance program objectives are (AIRLINES FOR AMERICA, 2015):

1. To ensure realization of the inherent safety and reliability levels of the aircraft
2. To restore safety and reliability to their inherent levels when deterioration has occurred
3. To obtain the information necessary for design improvement of those items whose inherent reliability proves inadequate
4. To accomplish these goals at a minimum total cost, including maintenance costs and the costs of resulting failures

Besides safety aspects, the MSG-3 analysis evaluates the operational and cost consequences of failures. The MSG-3 encompasses procedures and guidelines for systems, structures, zonal, and Lightning and High-Intensity Radiate Fields (L/HIRF) protection maintenance analysis.

The advisory circular 121-22 (C) and the MSG-3 methodology provide the process and rules for developing the initial MRB/MTB report containing the minimum maintenance requirements to assure the continued airworthiness of aircraft (UNITED STATES, 2012).

Initially, before the launch of the Boeing 777 program, the intervals of tasks were defined by using a pre-packaging concept in a way that, each task had its interval established in letter check, A, B, C, D, and multiples. After that, the concept changes, and each task is defined with its particular interval. The intervals can be in Flight Hours (FH), Flight Cycles, Landings (LD), Engine Hours (EH), APU Hours (AH), or Calendar based in Month (MO) or YEAR (YR), according to the predominant usage parameter. Some tasks may have their interval defined in more than one unit.

2.2.2 Development of MSG-3 System Analysis

The method for determining maintenance requirements for aircraft systems uses a progressive decision logic. The Evaluations are performed for each system Maintenance Significant Item (MSI), based upon their functions, the functional failures consequences and the failure causes.

The Figure 2.4 presents the summary of the MSG-3 analysis applicable to System and PowerPlant.

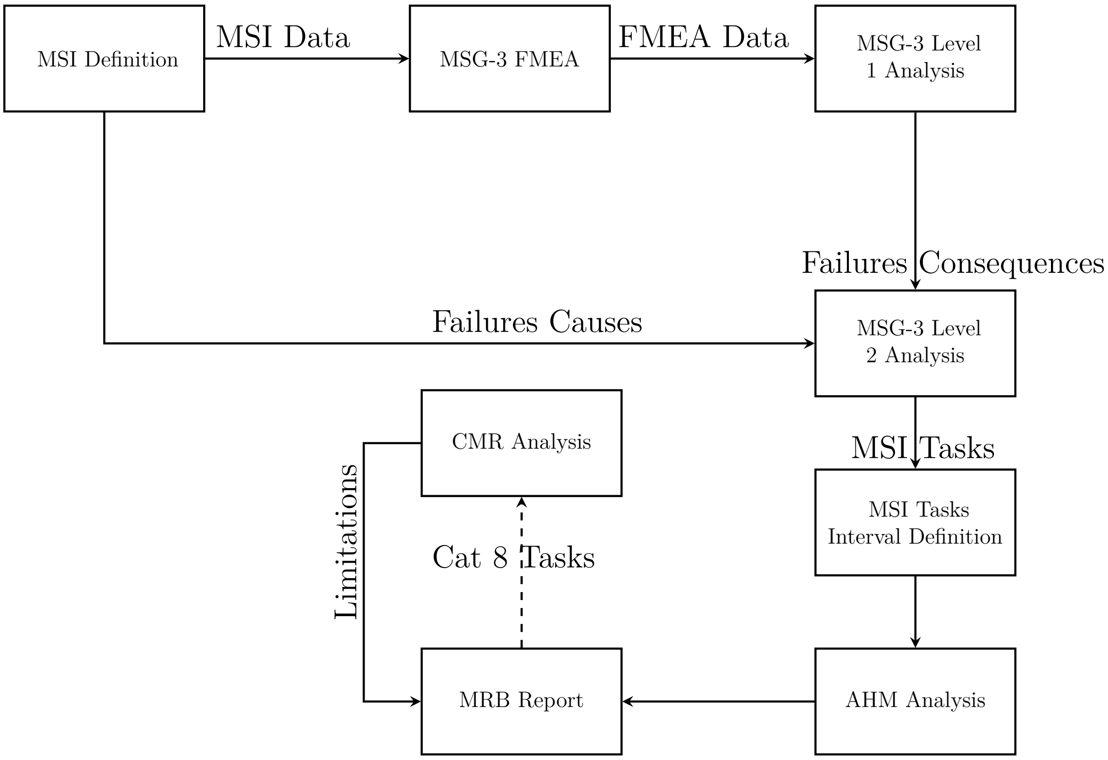


FIGURE 2.4 – MSG-3 System Analysis Process

The process of defining tasks and intervals for the System and PowerPlant may be outlined in the following steps (AIRLINES FOR AMERICA, 2015):

1. Definition of maintenance significant item (MSI); that could be a system, subsystem, or component whose failure could be hidden or could have an adverse effect on Safety, Operation, or a significant economic impact. MSI candidates are derived from the system top-down approach and they are defined normally at sub-system level.

2. Definition of the Functions, Functional failures, Failure Effect and Causes for each Maintenance Significant Item (MSI) to be analyzed.

3. Failure effect analysis (MSG-3 level 1) to categorize the consequences of failures as Evident/Safety (FEC 5), Evident/Operational (FEC 6), Evident/Economic (FEC 7), Hidden/Safety (FEC 8) or Hidden/Non-Safety (FEC 9). For safety categories a maintenance task is mandatory and, for the operational and economic categories a task may be desirable according to the impact in the operation and costs.

4. Failure Cause Analysis (MSG-3 level 2) based on the failures consequences and failure causes. The task definition MSG-3 (level 2)analysis provides an oriented logic to choose an applicable and effective task from the most straightforward and cheapest Service/Lubrication task to a most complex and expensive Restoration tasks. Item failure characteristics help defining the type of task that better fits the applicability criteria on the Table 2.1.

5. Definition of task interval for each task created in the previous step. It is considered the task type, related components failure and degradation behavior, reliability data, and the guidelines for each task type presented on the Table 2.2.

6. The Aircraft Health Monitoring (AHM) process aims to assess the capabilities AHM in order to determine the most effective ways for its utilization as a preventive measure or as a complementary tool to existing task. Each installed AHM feature associated to the task is examined in terms of its power to fully or partially substitute the work.

7. Tasks classified as hidden and safety (cat. 8) are considered by the Certification Maintenance Coordination Committee(CMCC) to support the Certification Maintenance Requirements (CMR) definition. It is evaluated, according to the CMCC approved criteria, if the MSG-3 task can preclude a CMR candidate. Final CMR requirements are included in the Maintenance Review Board (MRB) report as limitations. Normally, the CMR tasks are not considered for packaging and are controlled separately by operators.

2.2.3 Development of MSG-3 Structural Analysis

The Structural Program is mostly derived from an evaluation of the potential sources of damage that the aircraft structure may experience over its lifespan. Every Structural Significant Item (SSI) is evaluated based on its importance to the ongoing airworthiness, susceptibility to fatigue (FD), accidental (AD), and environmental (ED) damage, and the level of complexity in identifying such damage.

TABLE 2.1 – Applicability Criteria (AIRLINES FOR AMERICA, 2015)

Type	Applicability
SVC/LUB	The replenishment of the consumables must reduce the rate of functional deterioration
OPC/VCK	it must determine if the item is fulfilling its intended purpose (it does not require quantitative tolerances)
FNC/INP	Reduced resistance to failure must be detectable, and there exists a reasonably consistent interval between a deterioration condition and functional failure.
RST	The item must show functional degradation characteristics at an identifiable age and a large proportion of units must survive that age. It must be possible to restore the item to a specific standard of failure resistance
DIS	The item must show functional degradation characteristics at an identifiable age and a large proportion of units are expected to survive that age

TABLE 2.2 – Interval Definition Guidelines (AIRLINES FOR AMERICA, 2015)

Type	Guideline
SVC/LUB	The interval should be based on the consumable's usage rate, the amount of consumable in the storage container (if applicable) and the deterioration characteristics.
OPC/VCK	Consider the length of potential exposure time to a hidden failure and the potential consequences if the hidden function is unavailable
FNC/INP	There should exist a clearly defined potential failure condition. The task interval should be less than the shortest likely interval between the point at which a potential failure becomes detectable and the point at which it degrades into a functional failure. (If the specific failure data is available, this interval may be referred to as the P to F interval)
RST/DIS	Intervals should be based on the "identifiable age" when significant degradation begins and where the conditional probability of failure increases significantly

The SSI is any detail, element or assembly which contributes significantly to carrying flight, pressure, ground and control loads and whose failure could affect the structural integrity necessary for the safety of the aircraft (AIRLINES FOR AMERICA, 2015).

Figure 2.5 presents the summary of the MSG-3 analysis applicable to aircraft structures.

The process to define the structural requirements according to the MSG-3 analysis is

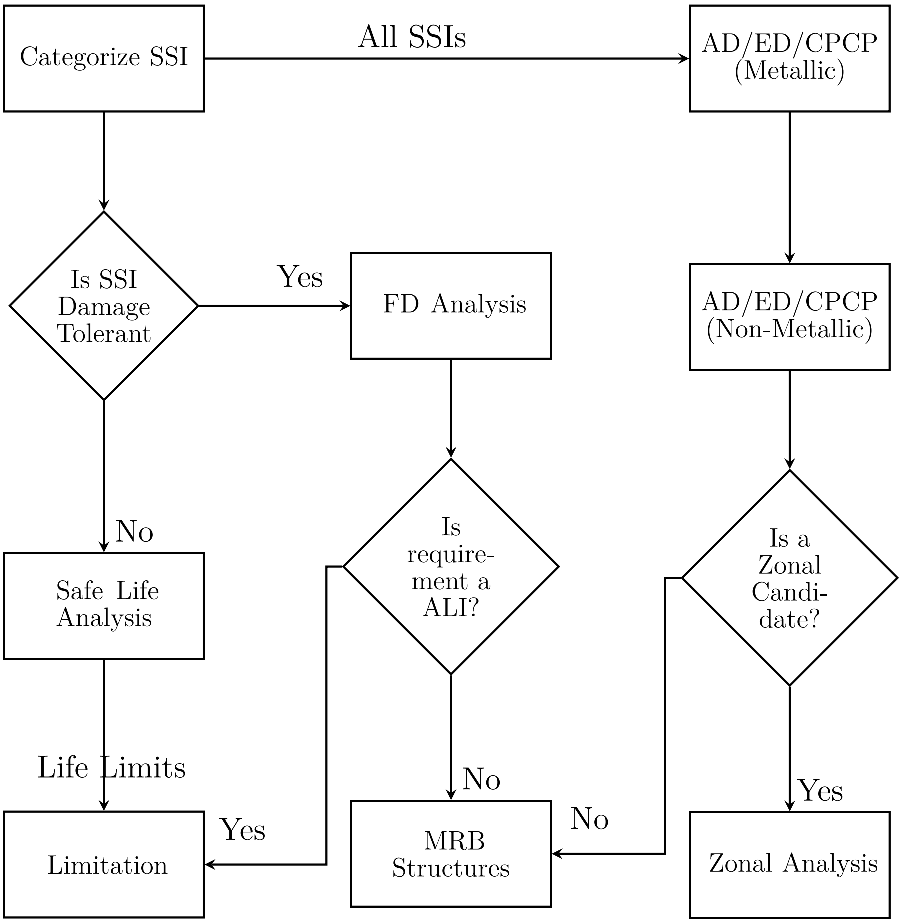


FIGURE 2.5 – MSG-3 Structural Analysis Process (Adapted from AIRLINES FOR AMERICA, 2015)

described by following steps:

1. Identification of aircraft structures and inspection regions, as well as the classification of structural significant items (SSI); structural components that are not categorized as SSI are referred to as "other structures" and are included in the Zonal inspection program..
2. An investigation of susceptibility to accidental damage (AD) and environmental damage (ED) is conducted on all metallic and non-metallic SSI. An investigation of susceptibility to accidental damage (AD) and environmental damage (ED) is conducted on all metallic and non-metallic SSI. The SSI undergo evaluation for potential inclusion in the Corrosion Protection and Control Program (CPCP) by analyzing the degree of environmental damage and considering the susceptibility of the region where the SSI located to corrosion.

3. The SSI may be categorized as either a Damage Tolerant or Safe Life item. Damage tolerant refers to a structure that can endure damage, and the remaining part of the structure can handle reasonable loads without experiencing structural failure or excessive deformation until the damage is identified. On the other hand, safe life refers to a structure that is not feasible to be designed or certified as damage-tolerant. Its reliability is ensured by setting discard limits, which remove items from service before fatigue cracking is anticipated.

4. Structural engineering determines the lifespan of each safe life SSI in accordance with RBAC 25.571. The limitations are outlined in the limitation section of the MRB.

5. A Damage Tolerance Analysis is formulated for every Damage Tolerant structure in order to establish the threshold and frequency of repeat inspections, as per the guidelines outlined in RBAC 25.571.

6. For Principal Structural Elements (PSE), an airworthiness limitation is established and the item is categorized as an Airworthiness Limitation Item (ALI), which is then included in the Limitation section of the MRB. PSE refers to a particular structural component, such as a detail, element, or assembly, that plays a significant role in supporting the loads experienced during flight, while on the ground, and during pressurization. It has been evaluated as being critical, meaning that if it were to fail, it could have a catastrophic impact on the overall structural integrity of the aircraft (as defined by RBAC 25.571). .

7. The MRB Structural section encompasses structural elements that do not fall under the categories of Limitations or candidates for Zonal analysis.

2.2.4 Development of MSG-3 L/HIRF Analysis

The purpose of maintaining Lightning / High Intensity Radiated Field (L/HIRF) protection systems is to minimize the likelihood of a single event, such as a lightning strike, and the occurrence of a failure that affects multiple channels of L/HIRF protection, such as accidental damage (AD) and environmental damage (ED), from compromising the airworthiness of the aircraft.

Lightning/HIRF Significant Items (LHSIs) refer to the components responsible for safeguarding important systems and structures from lightning occurrences and high-intensity radiated field frequencies. HIRF refers to non-ionizing electromagnetic energy that is generated externally to the aircraft. This energy falls between the frequency range of 10 kHz to 40 GHz and is created by devices like as radio transmitters, televisions, and radars. HIRF has the potential to create electromagnetic fields of great intensity.

Aircraft protection encompasses many measures such as the use of metal mesh for composite structures, radome and rudder tip diverters, anodized metal components, protection through rivet bonding, and termination of electrical harness shielding.

Figure 2.6 summarize the L/HIRF analysis process described below:

1. Identification of L/HIRF Aircraft Protections by location and zones of the aircraft.
2. Assessment of Environmental and Accident threats for each location.
3. Evaluation of L/HIRF protection degradation susceptibility based on the location threats.
4. Definition of L/HIRF task and interval considering the protection visibility and exposure to environmental and accidental damage.
5. Verification if the task can be eliminated based on the previous experience on similar projects, preclusion by the zonal tasks, or inclusion on the L/HIRF assurance program.
6. inclusion of resulting tasks on the L/HIRF section of the MRB.

2.2.5 Development of MSG-3 Zonal Analysis

The MSG-3 Zonal Analysis is often conducted following all prior analyses to assess the transferred items and the quantity of maintenance tasks occurring in a specific zone. The aim is to assess the elements that were not included in the previous analysis, such as duct lines, wiring, and other structures, which may contribute to a potential failure. The process involves conducting visual inspections in specific areas to assess the overall condition and safety of various system components and structural elements within those areas.

Zone assessment comprises two types of analysis: Standard and Enhanced Zonal. These are illustrated in Figure 2.7. In response to the investigation of the disaster on July 17, 1996, which involved a Trans World Airlines (TWA) Boeing 747, the Enhanced Zonal Analysis Procedure (EZAP) was implemented in MSG-3 Revision 2001.1. This update included the examination of the Electrical Wiring Interconnection System (EWIS). Based on examinations, presented by NTSB (2000), the most probable cause was a short circuit incident that resulted in the transmission of high voltage into the central wing tank through electrical connections.

The Zonal analysis summary is described in the following steps (AIRLINES FOR AMERICA, 2015):

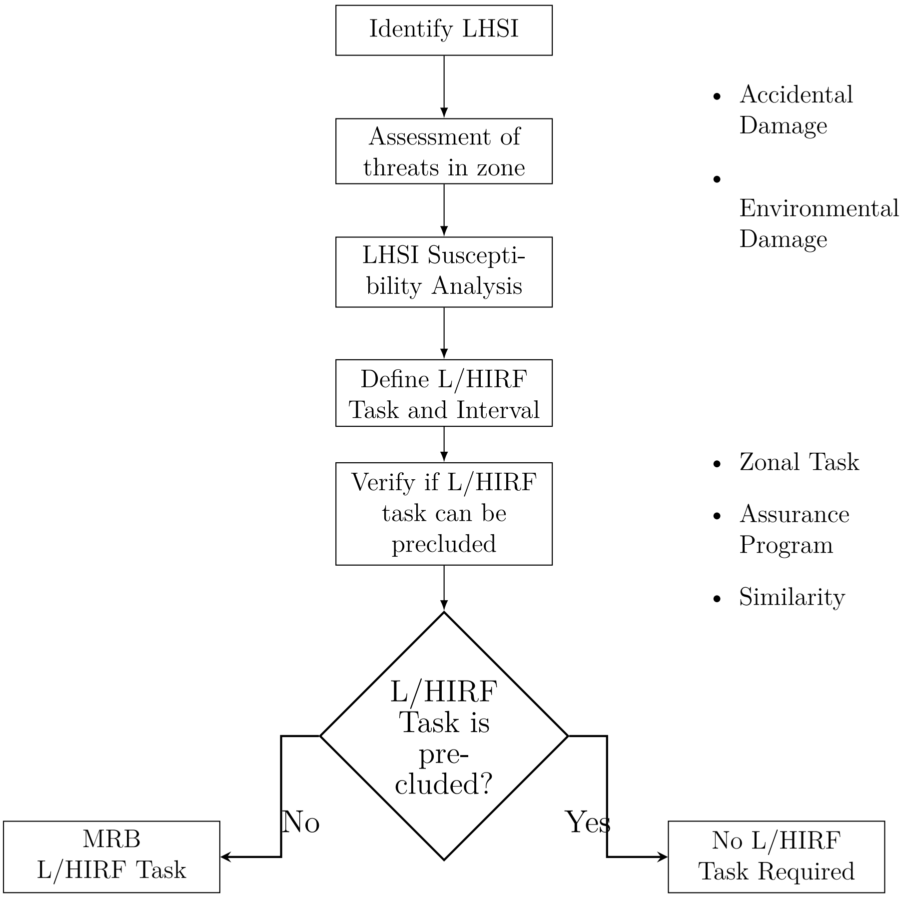


FIGURE 2.6 – MSG-3 L/HIRF Protection Analysis (Adapted from AIRLINES FOR AMERICA, 2015)

1. Division of aircraft into zones based on the ATA standard. The objective is to identify and document specific information on the zone, including access points, zone boudaries, and the presence of installed items such as equipment, protections, EWIS (Electrical Wiring Interconnection Systems), hoses, and ducts.

2. Verification of the presence of wire in the area. The zones that do not contain wire are merely subject to the standard zonal analysis. Both Standard and Enhanced zonal analysis are applied to zones that contain wirings.

3. The zone will undergo evaluation using the Standard analysis rating system, which takes into account its "Density" and "Importance" features. "Density" quantifies the degree of clustering in the zone, while "Importance" examines the relevance of the components installed in the zone for safe and efficient operation. "Exposure" is the measurement of how much an area is subjected to extreme temperatures, vibrations, atmospheric conditions, and the possibility of inadvertent damage to systems or structures.

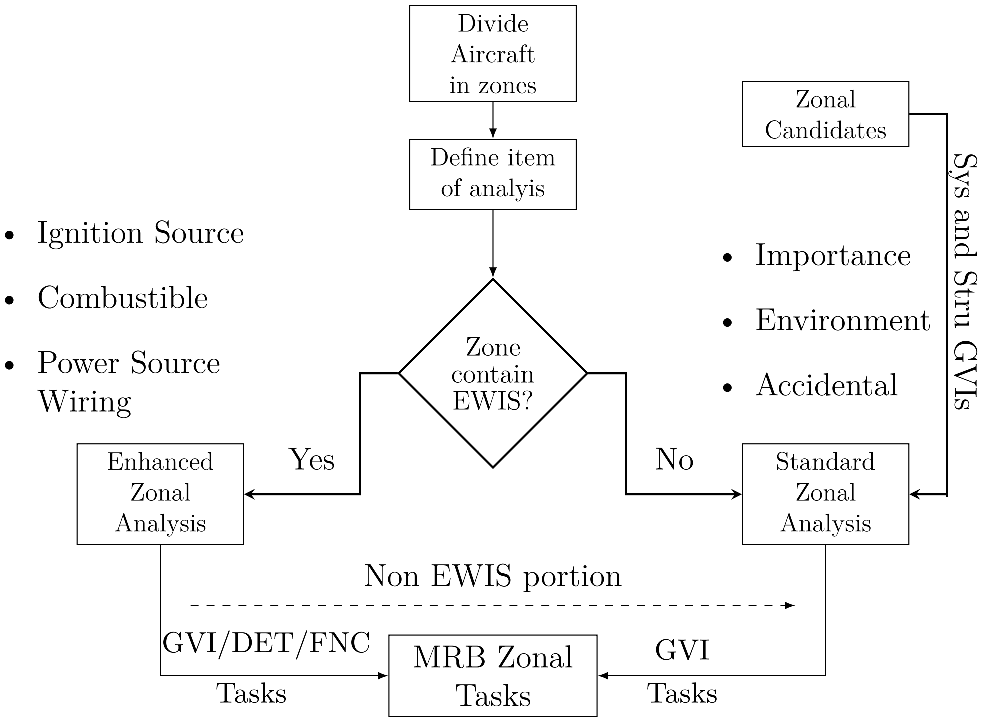


FIGURE 2.7 – MSG-3 Zonal Analysis.

4. Assessment of the zone using the Enhanced Zonal Analysis. Initially, the area is evaluated to determine the probability of containing flammable substances. If the answer is affirmative, the prevention of the buildup of flammable substances in the vicinity is regarded as the definition of a Restoration task to clean the area periodically. Subsequently, the evaluation proceeds in accordance with the instructions outlined in step 7.

5. If the presence of combustible material is not expected, the wiring in the zone is evaluated for the proximity to both primary and back-up hydraulic, mechanical, or electrical flight controls. In the case that there is no proximity to these items, the zone is subjected only to standard analysis. Otherwise, the assessment continue to the next step.

6. Determining the appropriate level of wire inspection by assessing the size, density, and probable fire hazards inside a given zone. The zone may require additional standalone General Visual Inspection (GVI), Detailed Inspection (DET), or a mix of both, depending on the results.

7. Definition of the task interval of the additional requirements based on the hostility of environment and likelihood of accident damage.

8. Incorporation of final requirements into the Zonal section of the MRB. The needs

for Dedicated Restoration, stand-alone GVIs, and DETs, which have been identified through the use of Enhanced Zonal Analysis, are kept as separate jobs in the appropriate section of the MRB.

2.3 Maintenance and Dependability Factors

Kinnison (2004) defines maintenance as the *Process of ensuring that a system continuously performs its intended function at the designed level of reliability and safety.*

The definition brought up an important point, which is that maintenance is intended to maintain or restore the asset's reliability to its design-in level. It indicates that maintenance cannot enhance the system's inherent dependability (BASSON, 2018).

The significance of efficient maintenance in attaining targeted levels of availability is noteworthy, as it preserves the inherent reliability and minimizes the time required for repairs (SMITH, 2017). Rebaiaia and Ait-kadi (2021) adds that the maintenance plan chosen for a component or multi-component system can have a substantial impact on reducing costs and decreasing downtime.

O'Connor and Kleyner (2012) provided a summary stating that the most effective preventive maintenance plan is determined by analyzing data on the parameters of the component's time-to-failure distribution, the costs associated with preventive maintenance, and the costs associated with system or component failure and repair. The data are derived from the projected dependability and maintainability attributes of the system and undergoes changes during the development and operational stages.

Therefore, as seen in Figure 2.8, an effective maintenance strategy, determined by Reliability Centered Maintenance (RCM) analysis, relies on the level of dependability in the design of the item and the simplicity of its maintenance based on its maintainability attributes. Increased dependability of components leads to less maintenance operations, whereas improved maintainability necessitates fewer maintenance logistical resources.

Reliability is defined as the *probability that a component or system will perform a required function for a given period of time when used under stated operating conditions* (EBELING, 2010), this implies some aspect that should considered during the system design, such that the user performance requirements and context of operation.

The distribution that defines a probability to each value of a continuous random variable can be described by the probability density function (PDF), represented by $f(x)$. The probability density function generates a curve that accurately depicts the form of the probability distribution.

A cumulative distribution function (CDF) is a mathematical function that provides

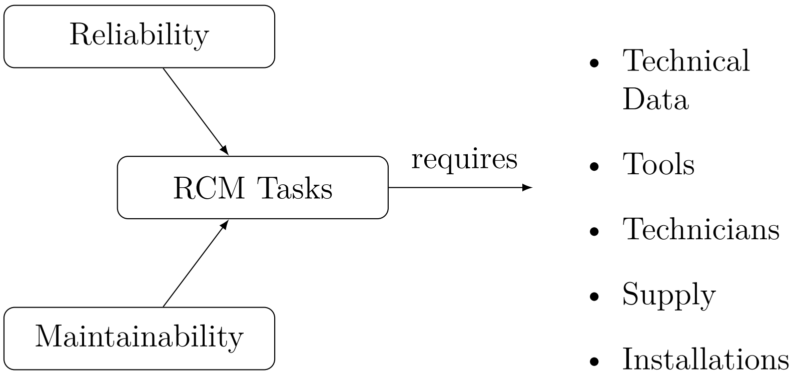


FIGURE 2.8 – Maintenance and Dependability Factors.

the cumulative probability of a random variable X being less than or equal to a given value x, denoted as $P_r(X \leq x)$. The CDF is represented by the function $F(x)$.

The reliability of an item, denoted by the probability that it successfully performs its intended function within a certain time period t, may be mathematically represented as $R_t = P_r(T \geq t)$. This implies that the duration till failure at a specific moment t is equal to or longer than t.

The failure cumulative distribution function $F(t) = 1 - R(t)$ is defined so that $F(0) = 0$ and $\lim_{t \to \infty} F(t) = 1$. It represents the likelihood that a failure will occur before time t.

In this case, the probability density function (PDF) is given by (EBELING, 2010):

$$f(t) = \frac{dF(t)}{dt} = - \frac{dR(t)}{dt} \tag{2.1}$$

and has the following property:

$$\int_0^{\infty} f(t)\ dt = 1 \tag{2.2}$$

The reliability $R(t)$ and the failure cumulative distribution $F(t)$ functions can be represented by the area under the $f_{(t)}$, where:

$$F(t) = \int_0^{t} f(t^{`})\ dt^{`} \tag{2.3}$$

$$R(t) = \int_t^{\infty} f(t^{`})\ dt^{`} \tag{2.4}$$

Another reliability metric commonly employed in maintenance studies is the Mean Time to Failure (MTTF). This metric represents the average or anticipated value of the

Probability Density Function ($f(t)$) and serves as a measure of central tendency for $f(t)$.

$$MTTF = \int_0^\infty t\ f_{(t)}\ dt \tag{2.5}$$

or,

$$MTTF = \int_0^\infty R_{(t)}\ dt \tag{2.6}$$

Mean Time to Failure (MTTF) is a reliability metric that applies to items that cannot be repaired, whereas Mean Time Between Failure (MTBF) is the average time for repairable items to fail and then return to service after being fixed.

Another noteworthy function examined in this work is the failure rate or hazard rate function. It offers an immediate measure of the frequency of failures. The failure rate function is shown by Ebeling (2010) to be provided by:

$$\lambda(t) = \frac{f(t)}{R(t)} \tag{2.7}$$

The average failure rate $\bar{\lambda(t)}$ between t_1 and t_2 is given by the equation below:

$$\bar{\lambda}(t) = \frac{1}{t_2 - t_1} \int_{t_1}^{t_2} \lambda(t^{‘})\ dt^{‘} \tag{2.8}$$

The Reliability function can be defined in relation to the $\lambda(t)$ by the equation below:

$$R(t) = \exp\left[-\int_0^t \lambda(t^{‘}) dt^{‘}\right] \tag{2.9}$$

The failure rate function can either increase (IFR), decrease (DFR), or remain constant (CFR) in relation to the operating time. An item may exhibit these three qualities throughout its lifespan, with a behavior that conforms to the conventional bathtub curve.

The results of the research undertaken by United Airlines officials, as depicted in the Figure 2.3, demonstrated that the majority of these components (89%) did not show any benefits when exposed to a limitation based on their operational lifespan. Merely a small proportion (4%) conformed to the bath-tube curve. (SMITH; HINCHCLIFFE, 2003)

The maintenance requirements are established by analyzing the time-to-failure distribution, failure types, degradation characteristics, and the consequences of a failure on operational performance and safety.

Each requirement's maintenance activity entails a certain amount of labor hours, including tasks such as opening and closing accesses, preparing for the work, and utilizing tools and test equipment. These demands are closely correlated with maintainability factors.

The maintainability (M) is an *inherent characteristic of system or product design. It pertains to the ease, accuracy , safely, and economy in the performance of maintenance actions* (BLANCHARD *et al.*, 1995). As stated by Ebeling (2010), maintainability refers to the likelihood of successfully restoring or repairing a failing system to a specified condition within a certain period of time, provided that maintenance is carried out using standard procedures.

An commonly used metric of maintainability in supportability analysis is the Mean Time To fix (MTTR), which represents the average time it takes to fix a system.

$$MTTR = \frac{total\ repair\ maintenance\ time}{number\ of\ repair\ activities} \tag{2.10}$$

Another metric used to assess maintainability is Mean Preventive Maintenance Time (MPMT), which is determined by calculating the average duration of preventive maintenance activities.

$$MPMT = \frac{total\ preventive\ maintenance\ time}{number\ of\ preventive\ activities} \tag{2.11}$$

According Ebeling (2010), for a system composed of n distinct components j, the Mean Time to Repair of the system $MTTR_{sys}$ is given by weighted average of component Mean Time to Repair, $MTTR_j$, and it can be calculated by:

$$MTTR_{sys} = \frac{\sum_{j=1}^{n} fc_j \times MTTR_j}{\sum_{j=1}^{j}\ fc_j} \quad for\ j \in \{1, 2, 3, \ldots, |N|\} \tag{2.12}$$

Where fc_j is the expected number of failure of $item_j$ along the operating time. For items with a constant failure rate the fc_j is represented by λ_j, and N is the set of system components.

Similarly, the mean preventive maintenance time of the system ($MPMT_{sys}$) is given by weighted average of mean preventive maintenance time, $MPMT_i$:

$$MPMT_{sys} = \frac{\sum_{i=1}^{k} fp_i \times MPMT_i}{\sum_{i=1}^{k}\ fp_i} \quad for\ i \in \{1, 2, 3, \ldots, |K|\} \tag{2.13}$$

Where, fp_i is the frequency of i preventive maintenance given by:

$$fp_i = \frac{1}{Tprev_i} \tag{2.14}$$

and K is the set of system preventive maintenance.

The system active mean maintenance time ($\overline{M}$) is calculated by considering both corrective and preventive mean maintenance times. For a system with N components and K preventive maintenance stoppages, ($\overline{M}$) is calculated as follows:

$$\overline{M} = \frac{\sum_{j=1}^{N} fc_j \times MTTR_j + \sum_{i=1}^{K} fp_i \times MPMT_i}{\sum_{j=1}^{N} fc_j + \sum_{i=1}^{K} fp_i} \tag{2.15}$$

or, considering a constant failure rates, ($\overline{M}$) is given by:

$$\overline{M} = \frac{\sum_{j=1}^{N} \lambda_j \times MTTR_j + \sum_{i=1}^{K} fp_i \times MPMT_i}{\sum_{j=1}^{N} \lambda_j + \sum_{i=1}^{K} fp_i} \tag{2.16}$$

The final preventive maintenance plan is driven by two inherent design qualities, reliability and maintainability. These characteristics have an impact on the amount and in the frequency of preventive maintenance tasks, which in turn affect the costs associated with labor, material, and system availability (A).

The concept of Availability (A) is defined by Ebeling (2010) as the *Probability that a system or component is functioning as required at a specific moment or during a specified time period, when operated and maintained according to prescribed guidelines.* It is often observed that:

$$Availability\ (A) = \frac{uptime}{uptime + downtime} \tag{2.17}$$

This thesis addresses two availability measures, namely the inherent availability and the achieved availability, which do not account for the period when systems are unavailable due to administrative and logistics concerns.

The inherent steady-state availability A_I considers only the time spent in the corrective maintenance and is given by:

$$A_I = \frac{MTBF}{MTBF + MTTR} \tag{2.18}$$

Additionally, the Achieved Availability A_A includes the preventive maintenance time and it is computed by:

$$A_A = \frac{MTBM}{MTBM + \overline{M}} \tag{2.19}$$

Where $\overline{M}$ is Mean Maintenance active time calculated above, and the $MTBM$ is the

Mean Time Between Maintenance which can be calculated by:

$$MTBM = \left[\frac{1}{\sum_{j=1}^{N} \lambda_j + \sum_{i=1}^{K} fp_i}\right] \tag{2.20}$$

This study calculates the achieved availability, denoted as A_A, after optimizing the packing and sequencing of tasks.

2.4 Maintenance data and costs

2.4.1 Maintenance Data

When dealing with a newly designed system, it is reasonable to use data from an existing system that is similar in nature (O'CONNOR; KLEYNER,2012;GONCALVES; TRABASSO,2018). Furthermore, the initial assessment of dependability can be determined based on data obtained from standard guidelines and data obtained from military or commercial aircraft benchmarks. As the development of the product advances, the outcomes of various tests conducted on its components, such as the highly accelerated life test and highly accelerated stress screen tests (HALT/HASS), aircraft flight and ground tests, and task maintainability validation, could require changes in the system and/or impact the projected data utilized.

The reliability growth program closely monitors the initial reliability information during the development phases. Its primary goal is to enhance reliability over time by modifications in design, manufacturing methods, and procedures (EBELING, 2010).

The maintainability data utilized for development and optimization are derived from the maintainability task analysis and mostly consists of expected information regarding the required man-hours and materials for the preparation and execution of the maintenance work. The predictability of a system's maintainability relies on a certain design configuration that has the potential to be altered during the creation of the product.

As mentioned by Blanchard and Blyler (2016), periodic evaluations are essential at designated design review stages or with each design change during the system development process to guarantee the fulfillment of system reliability and maintainability requirements.

During the operation phase, a program is designed to control the dependability. As stated by Kinnison (2004), this program involves a set of rules and approaches designed to efficiently supervise and control the operational and maintenance parts of a product. The main objective of this system is to monitor and evaluate performance, as well as send notifications if any remedial actions are deemed essential. Moreover, it provides the essential information to facilitate the adjustment of the maintenance plan.

Operators in the aeronautical business are required by the Federal Aviation Administration (FAA) under Part 121.373 to have a continuing analysis and surveillance system (CASS). The aim is to ensure the effectiveness of maintenance and inspection programs. In addition, the FAA AC 121-22(C) includes a section entitled *Implementation and Optimization of Task Interval* that provides guidelines for data collection and statistical analysis. These guidelines are intended to be followed by aircraft manufacturers and operators to improve their product maintenance plan intervals. The Figure 2.9 illustrates the primary stages of the methodologies employed in the evolution process:

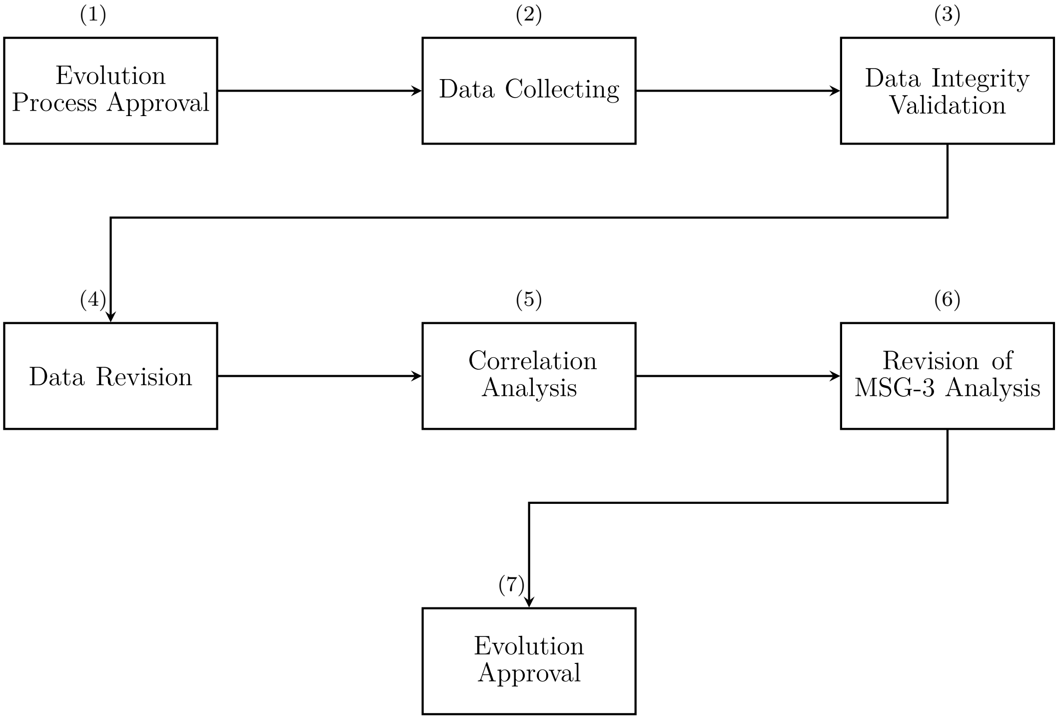


FIGURE 2.9 – Evolution Process (Adapted from UNITED STATES, 2012)

(1) Before commencing optimization efforts, the manufacturer must inform the certification authority of their intention to enhance the maintenance plan and acquire its approval. The authorized procedure is thereafter incorporated into the policy and procedure handbook (**PPH**), which will provide the instructions to be followed by all participants.

(2) The necessary data is collected following the strategy and criteria stated by the PPH. A comprehensive method must be created to gather data, guaranteeing its quality, completeness, and reliability, while also facilitating traceability and auditability of the data. To guarantee the quality and accuracy, it is crucial to use data derived from the operator's task completion outcomes and presented in a format specified by the regulatory authority. The ATA SPEC 2000 Chapter 11 is a commonly employed framework for transmitting maintenance reliability information in the aeronautical industry. The operators are required to transform any data that does not conform to the accepted standard into the required format. Regarding data quality, it is imperative for the manufacturer to ensure that the field data obtained is accurately provided by the operators and encompasses all the necessary information for the evaluation process, encompassing:

- Aircraft serial number, age since delivery in calendar days, flight hours and cycles;
- Geographical and operational environmental;
- Number of tasks accomplished with their intervals, failure effect category and, preventive maintenance findings;
- Components shop findings;
- Unscheduled maintenance reports;

(3) The assurance of data integrity is contingent upon the implementation of a validation and audit system that facilitates the secure transfer, storage, and retrieval of data inside the database, while preventing any unauthorized actions such as insertion, alteration, or deletion.

(4) The data revision process involves analyzing the time-frame and quantity of data, as well as considering the existing field experience. This is done to ensure that a desired confidence level of 95% is achieved. The statistical analysis is conducted in a task-by-task manner to provide the rationale for the attained level of confidence. The data review process encompasses also an engineering study of both routine and non-routine finding results, evaluating their importance and severity that would impact the evolution. This evaluation also takes into account the pilot (PIREPS) and the reliability program reports, and the modifications implemented by Service Bulletin or Airworthiness directives, on the system and components being analyzed.

(5) The correlation analysis accounts on the Mean Time Between Unscheduled Removal (MTBUR), failure data analysis and all others pertinent data that could influence on the preventive maintenance results. Changes on maintenance task interval should be validated based on the quality and quantity of data.

(6) The proposal of changes are evaluated internally at OEM, and requires the revision of the MSG-3 analysis to be reviewed by the maintenance working groups and finally submitted to the industry steering committee (ISC) and authorities for the final approval.

(7) The MRB Report revision proposal is submitted to certification authorities for the final approval and distributed to all operators.

This endeavor is noted to commence only after a significant period of operation, as a reactive response, when the manufacturer or operators realize that the product is facing a decrease in competitiveness. The dynamic changes and evolution of data throughout the development or operation phases might create useful information for implementation of a proactive maintenance plan updates.

Many sets of field data are produced during maintenance (process maintaining) and operation activities. A framework for a resilient maintenance plan would collect, analyze, and evaluate data to proactively spot areas where the present maintenance strategy can be improved.

Resilience in this context refers to the ability to closely monitor the maintenance record and detect any decline in the effectiveness of maintenance operations. It involves promptly and systematically identifying areas that require revision in the maintenance program, while ensuring economic sustainability.

2.4.2 Life Cycle and Maintenance Costs

The life cycle cost (LCC) analysis includes all future costs associated with research and development, investments (in manufacturing, construction, and initial logistics), operations, maintenance and, system disposal (BLANCHARD; BLYLER, 2016). The LCC is the sum of each cost parcels involved in the actions and resources for accomplishment of each life cycle phase. The LCC model furnishes a complete figure of the cost involved in the whole life of the project. LCC can be divided in four major parcels of costs as presented in the Figure 2.10.

The maintenance cost is a component of the Operation and Maintenance costs and encompasses all expenditures related to the ongoing operation and maintenance support of the system during its entire lifespan. Based on Fabrycky and Blanchard (1991) and empirical evidence, operation and maintenance expenses constitute a significant portion, surpassing 60%, of the total life cycle costs (LCC). It is important to acknowledge that in certain development processes, the LCC is not considered comprehensively, disregarding the importance of these expenditures. It is now essential to assess the effectiveness of all logistical aspects and financial obligations associated with the launch of a new product

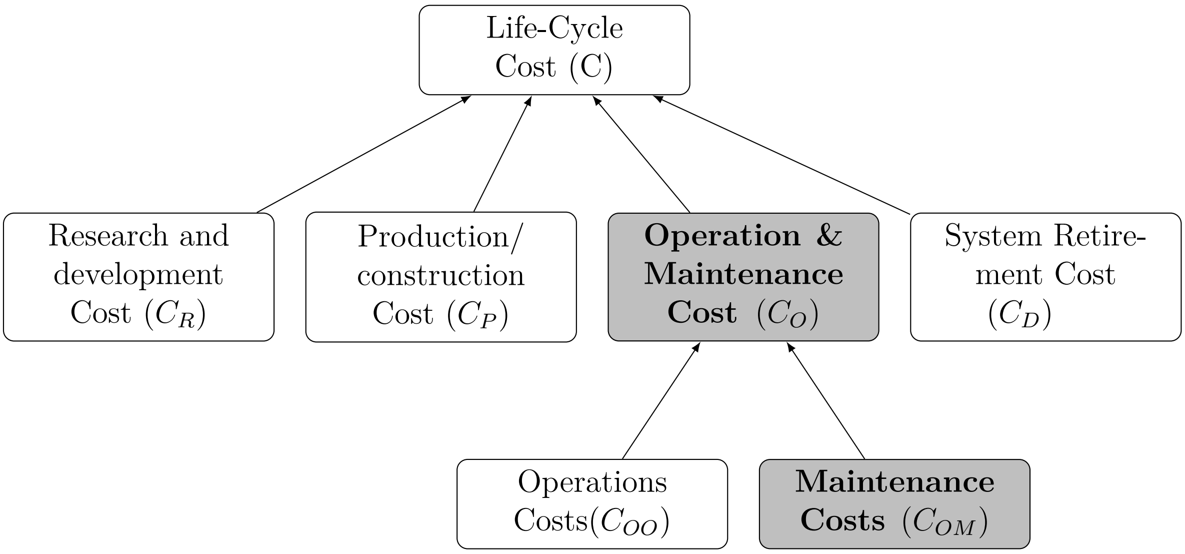


FIGURE 2.10 – LCC Categories (Adapted from BLANCHARD, 2004)

or system in order to guarantee its efficiency during the operational period.

An additional noteworthy aspect is to the fact that decisions made during the initial stages of development, typically characterized by limited maturity and product knowledge, exert a significant influence on the expenses incurred throughout the life cycle. Over 50% of the planned LCC has been committed up to the stage of concept development and preliminary design.

Table 2.3 presents the breakdown and allocation of the all LCC components, while the maintenance expenditures categories are depicted in the Table 2.4:

TABLE 2.3 – Life Cycle Costs (LCC) structure (BLANCHARD; BLYLER, 2016)

Components	Cost Parameters
Research & development (Cr)	Program management, Engineering design, Advanced development, Prototype development, Test & evaluation, Engineering Data/Information, Supplier activity
Production & Construction (Cp)	Manufacturing, Material inventories, Construction, System test & evaluation, Quality control, Logistics support
Operation & maintenance (Co)	System operation, Maintenance support, Logistics support
System retirement (Cd)	System retirement activities

TABLE 2.4 – Maintenance Cost (COM) Categories (BLANCHARD; BLYLER, 2016)

Category	Definition
COMM	Maintenance personnel and support at Organizational, Intermediate, Depot and Supplier Levels.
COMX	Spare/repair parts at Organizational, Intermediate, Depot and Supplier Levels.
COMS	Test and support equipment maintenance
COMT	Transportation and handling
COMP	Maintenance training
COMF	Maintenance facilities
COMO	Technical data

The classification of each life cycle cost component can be determined based on its characteristics in the following manner (FABRYCKY; BLANCHARD, 1991):

1. Recurring and Non-recurrent Costs
    - *Recurring Cost*: refers to those costs that occur repeatedly during the life cycle. This kind of cost occurs mainly during the in-service phase and includes costs of maintaining and support the system operation. Also, the labor and material costs related with the production of items may be classified as recurring cost.
    - *Nonrecurring Cost*: it is usually a one-time cost. Example are costs related to the engineering design and development, testing, acquisition of manufacturing tools, construction of facilities, and so on.
2. Direct and Indirect Costs
    - *Direct Cost*: The phrase "direct cost" refers to the expenditures that are explicitly related to activities that may be directly attributed to the system or product. This incorporates the costs associated with the materials and labor used in the production and assembly of the product. Additionally, it includes the work hours of mechanics involved in performing maintenance, as well as the consumables and materials consumed during the execution of maintenance task for the product. Also, the costs associated with subcontracting may also be included.
    - *Indirect Cost*: It refers to costs that cannot be explicitly associated with the product. Examples include costs associated with administration and supervision, as well as expenses associated with employees, such as compensation, group insurance, pensions, and holidays.

3. Fixed and Variable Costs

    - *Fixed Cost*: is a cost which the total does not variate during a period of time, it does not depends on the level of operational activity, or the quantity product delivered. Costs related to depreciation, taxes, insurance, interested on invested capital, sales program, and research can be included in this category.
    - *Variable Cost*: It refers to group of costs which vary with the level of operational activity. Example, fuel, oil, maintenance and crew costs change in proportion to aircraft usage. In manufacturing the the cost of material and labor will vary according to the quantity of units produced.

In the civil aeronautical industry, from the operator´s viewpoint, the life-cycle costing (LCC) can be divided into three important parcels: acquisition cost (aircraft price); direct operating cost (DOC); and indirect operating cost (IOC) (MINWOO *et al.*, 2019). It is worth mentioning that, while the DOC is related to the aircraft characteristics, the IOC is directly influenced by the airline operation and maintenance strategies.

The International Civil Aviation Organization (ICAO) has the objective of permitting the sustainable growth of global civil aviation. The ICAO produces policies and standards that must be followed by its member states. For the airline´s cost analysis the ICAO establishes the parameters that should be reported by the members (KOCH, 2013). The Total Airline Operating Cost model is used by ICAO members worldwide in the airline industry. The costs parcels in the TOC can be classified as Direct (DOC) or Indirect (IOC) Operating Costs. Table 2.5 lists the TOC parameters and their classification

ICAO defines DOC as those costs incurred in operating the aircraft, which include the costs of flight operations, flight equipment maintenance and overhaul, flight equipment depreciation, and airport plus en-route air navigation charges. These costs are also denominated Airplane Related Operating Costs (AROC) (BELOBABA *et al.*, 2015)

The distribution of cost reported by the major airlines in the United States, as shown in the 2013 report from the Airline Cost Management Group, is depicted in Figure 2.11.

According to the criteria provided by ICAO (2017), the aviation sector categorizes the Total Operating Cost into three distinct components: Flight Direct Operating Cost (DOC), Ground Operating Cost, and System Operating Cost as shown in Table 2.5.

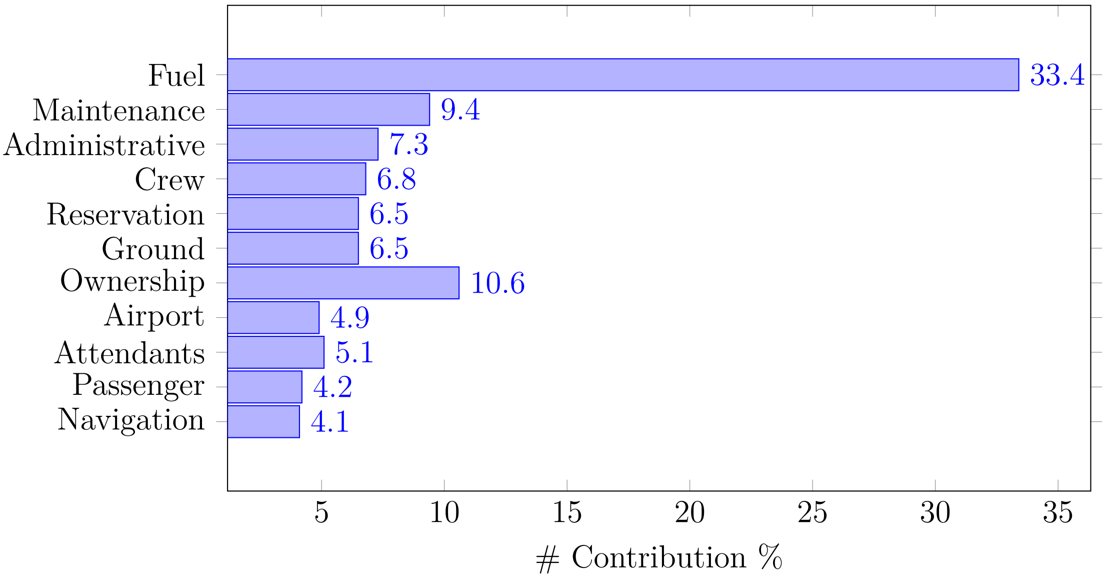


FIGURE 2.11 – Total Airline Operating Cost (IATA, 2018)

TABLE 2.5 – Total Operating Cost Categories (ICAO, 2017)

Components	Cost Parameters
Flight Operating Cost	Cockpit and cabin crew, fuel, Maintenance, Ownership (depreciation, insurance, investments, leasing)
Ground Operating Cost	Aircraft services at airport stations, Passenger services at airport stations, Reservations/sales charges, Landing fees
System Operating Cost	Marketing, Administrative and Overhead items, In-flight services, Ground equipment ownership

The Direct Operating Cost (DOC) encompasses all expenditures associated with aviation operations such as, cockpit and cabin crew salaries, fuel costs, maintenance expenditures, and ownership-related financial costs including depreciation, insurance, leasing, and investments. Ground operating costs encompass various expenses associated with passenger services, reservation and sales charges, as well as aircraft landing fees at airport stations.

The flight operating cost rate is often expressed as a cost per flight hour ($ /FH), cost per flight cycle ($ /FC), or cost per block hour ($ /BH). The latter is a widely used industry metric for displaying operating cost data. As stated by Kinnison (2004), the block-hour is calculated from the moment the aircraft departs from the gate after the wheel chocks are removed, until the moment it arrives at the destination gate and the wheel chocks are put back in place.

In addition, airlines employ various indices to assess their performance and profitability. The total operating cost per available seat kilometer (CASK) is a frequently employed metric for assessing the effectiveness of a given operating route. The overall cost is divided by the airline's production of Available Seat-Kilometers (ASK). One ASK represents the measure of one seat that is available for one kilometer of flight. The ASK is contingent upon the aircraft's specific attributes, such as the quantity of seats available and the aircraft's capability for flying range (BELOBABA *et al.*, 2015).

The assessment of the efficiency of a certain operating route takes into account the passenger traffic, measured in terms of Revenue Passenger Kilometers (RPK), where each RPK represents the transportation of one paying passenger over a distance of one kilometer. Belobaba *et al.* (2015) defines the operating profit as total revenue minus total operating expense:

$$Operating\ Profit = (RPK \times Yield) - ASK \times CASK\ (Unit\ cost) \tag{2.21}$$

Where Yield, is a measure of the average fare paid by all passengers per kilometer flown.

An important concept used in thesis is the *Opportunity Cost (OC)*. According to Wieser (1984), OC represents the potential benefits an individual, investor, or business misses out on when choosing one alternative over another. Depending on the operating hours per day characteristic of an airline, one may establish the hourly opportunity cost (HOC).

The HOC is calculated in function of loss of revenue caused by the aircraft downtime and its impact on the ASK. For a better understanding, let's consider a certain airline operating in a certain country and having an average revenue per seat of $\$90.0/h$, and considering a 170 seat aircraft with an average of 140 occupied seats, which results in a total revenue of $\$12,600.0/h$. Also, considering a block-hour cost of $\$10,000.0/h$, this would give us a profit of $\$2,600.0/h$. If the aircraft is unable to fly, this number may be recorded as a HOC.

The maintenance cost, accounting for approximately 9.4% of the overall expenditure, includes the combined expenses associated with people and materials for both scheduled and unscheduled maintenance interventions at various levels within the organization, including organizational, intermediate, depot, and supplier levels. Additionally, the expenses associated with testing and supporting equipment, transportation and handling, facilities, and training necessary for the execution of product maintenance are encompassed within this category. It is widely acknowledged that expenditures related to maintenance activities are inevitable, as they are essential for fulfilling the ongoing airworthiness obligations.

These costs, are highly influenced by the aircraft maintainability, reliability, and maintenance plan checks defined during the product design. As mentioned by Camilleri (2018), factors including quantity and cost of labor and materials, components failure rates, location of facilities affects this parcel of cost.

The expenses associated with aircraft maintenance are significantly impacted by factors such as the aircraft's maintainability, reliability, and the maintenance plan inspections that are established during the product design phase. According to Camilleri (2018), during the operation phase, various factors such as labor and material costs, failure rates of components, facility resources and location, aircraft utilization, and aircraft aging influence the overall maintenance cost.

As stated by Wang *et al.* (2021), the overall expenses associated with maintenance can be categorized into two groups: direct maintenance costs (DMCs) and indirect maintenance costs (IMCs). Direct maintenance costs (DMCs) encompass expenses that are closely tied to the product itself. These costs primarily consist of the labor and materials directly utilized in the preventive and corrective maintenance activities performed on a system. On the other hand, indirect maintenance costs (IMCs) pertain to the maintenance environment surrounding the product, and encompass expenditures associated with facilities, tooling, engineering, planning and controlling, as well as training for the maintenance group.

The Direct Maintenance Costs (DMCs) for a certain time period can be determined by adding up the expenses for personnel and materials incurred during each maintenance event that occurs during that timeframe considered, and then dividing this sum by the total number of flying hours (FH). This includes both scheduled and unscheduled maintenance occurrences, both on the aircraft and within the maintenance facility. The final average maintenance cost at the end of the time period is represented as the maintenance cost per flight hour ($/FH) and may be calculated using Equation 2.22.

$$DMC = \frac{\sum_i \ (Maintenance\_Event\_Cost)_i}{\text{Total Flying Hours (FH)}} \tag{2.22}$$

There are others methods to calculate maintenance costs, such as cost per cycle, cost per year, and cost per seat. The prevailing unit of measurement is the cost per flight hour as it more accurately reflects the cost dynamics associated with fleet utilization.

A general illustration of the influence of the fleet utilization profile on maintenance costs over a 15-year period is shown in Figure 2.12. A set of maintenance requirements controlled in flying hours (FH) and months is considered in the example.

As seen in Figure 2.12, when an aircraft is under utilized, the average maintenance cost increases owing to the expenditures associated with scheduled checks based on calendar periods. The IATA Executive Airline Maintenance Cost Executive Commentary report for the year 2021 reveals that the maintenance costs incurred by 37 US airlines amount to $1,340 per flight hour, which is equivalent to $3,230 each flight cycle. According to IATA's Maintenance Cost Technical Group (2022), the aforementioned high figures can be linked to the US fleet's poor utilization during the 2021, which amounts to just 6.4 hours per day.

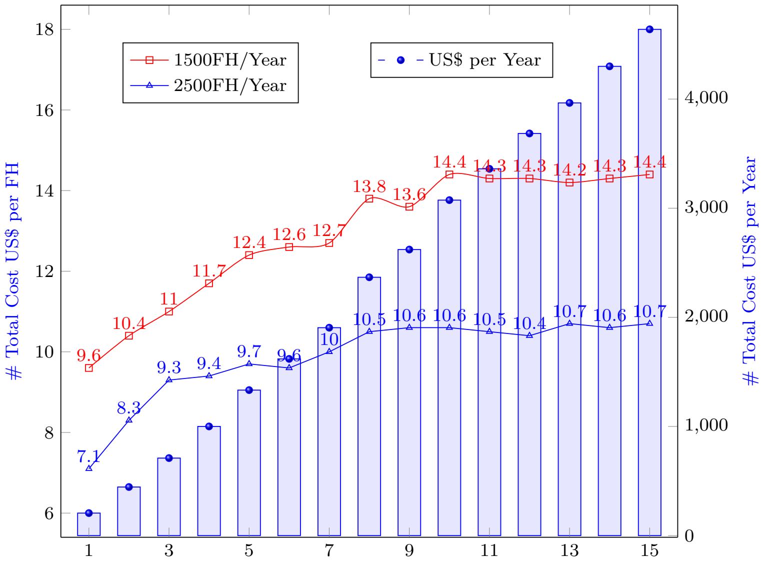


FIGURE 2.12 – Influence of Utilization Profile on Maintenance Costs

2.5 Optimization Methods

The desire to accomplish the most with the least amount of effort pervades most human actions (KULKARNI *et al.*, 2016). Optimization challenges arise in a variety of fields, including science, engineering, management, and business. As a fundamental principle, optimization supports the examination of numerous intricate decision-making or allocation issues (LUENBERGER; YE, 2008).

An optimization problem refers to a problem where the objective is to find the optimal solution from a range of feasible candidates solutions. Essentially, the purpose is to optimize an objective function by considering a set of constraints, with the aim of identifying the most favorable cost-benefit ratio for a given scenario (PASSARO; JUNIOR, 2019).

An optimization problem, according to Talbi (2009), can be defined by the couple (S, f), where S is a set of feasible points and $f : S \to R$ the objective function that has to be optimized. The objective function assigns a real value representing the worth of each solution $s \in S$ in the search space. The point s^* that leads to the best value of f is the solution of the optimization problem.

A global optimum solution $s^* \in S$ implies that it has a better objective function value than all others solution on search space. The search region is restrict by the constraints established by the problem circumstances.

In summary, the optimization problem can be formulated generally as a function of decision variables and in the presence of some constraints (RAYWARD-SMITH, 1996):

$Minimize\ f(\mathbf{x})$

$Subject\ to\ g_i(\mathbf{x}) \geq b_i;\ i\ =\ (1, \ldots, m)$

Where, $\mathbf{x}$ is a vector of decision variables and $f(.)$ and $g_i(.)$ are general functions.

Luenberger and Ye (2008) categorizes optimization problems into two types: linear and nonlinear programming. Additionally, the author categorizes nonlinear problems as either constrained or unconstrained.

When the constraints are made up of linear equalities and inequalities and the objective is linear in the variables, the problem is said to be linear programming (LP). According to Luenberger and Ye (2008), a widely used mathematical representation of an LP is expressed in compact vector notation as follows:

$Min\ c^T x$ or $Max\ c^T x$

subject to

$\mathbf{A}\ .\ \mathbf{x} \geq \mathbf{b}$

$\mathbf{x} \geq \mathbf{0}$

Where,

$\mathbf{A}$ is a mxn matrix and $\mathbf{b}$ is a $mx1$ vector.

If any of the functions between the objectives and constraints is nonlinear, the problem is referred to as a nonlinear programming (NLP) problem. The NLP problem is considered the most generic type of programming problem, with all other problems being subsets of it.

Several methodologies can be used to solve an optimization problem. Optimization methods can be classified as deterministic or stochastic methods.

The stochastic technique may be categorized into two subcategories: heuristics and approximation algorithms. Both techniques possess the ability to discover optimal solutions within an acceptable time frame.

According to Rayward-Smith (1996), a heuristic is a strategy that searches for good (i.e., near-optimal) solution at a reasonable computing cost but does not ensure optimality or feasibility.

Heuristics may efficiently identify satisfactory answers for large-scale issues, but they typically lack assurances on the accuracy of the solutions they provide. Approximation algorithms, in contrast, provide a sub-optimal solution that may be achieved in polynomial time, while also guaranteeing a constraint on the degree of sub-optimality.

Specific heuristics are meant to solve a specific problem or instance, while Metaheuristics are considered general-purpose algorithms that can solve virtually any optimization problem. According to Talbi (2009), in the last 20 years, metaheuristics have grown in prominence. Their employment in a variety of applications demonstrates their efficiency and efficacy in solving huge and complicated problems.

The use of a deterministic approach ensures that the answer obtained is the best possible solution within the limitations specified. To narrow down the search and find the best solution for a problem, it employs rigorous mathematical approaches. However, due to the exhaustive search or mathematical complexity required, they may have limitations in terms of scalability and efficiency for large-scale, complex situations. According to Talbi (2009), generally the exact methods guaranteed optimal solution, but it may take an exponential number of iterations to obtain it.

Talbi (2009) lists the following deterministic methods.

- Dynamic Programming is based on Bellman´s principle[1] to recursively divide the problem into sub problems.
- Constraint Programming is based on tree search and logical implications. In constraint programming, optimization issues are represented by a set of variables linked by a set of constraints.
- Branch and X family algorithms, developed by Searching Operation community, are based on an implicit enumeration of all solutions of the considered optimization problem. It includes the branch and bound, branch and cut, branch and price methods.
- A^* and IDA^* (**Interative Deepening Algorithms**), developed by the Artificial Intelligence community, also enumerates all solutions of an optimization problem.

This thesis employs an exact method, using a branch-and-cut technique to address the integer programming problem. The Integer programming (IP) involves problems in which all or some of the variables, x_i, are constrained to be integers. If some but not all variables are integer, it is called a Mixed-Integer Programming (MIP) (LEE; LEYFFER, 2011).

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[1] An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision.

Also, this work uses the First-Fit Decreasing approximation algorithm to sequence the tasks in the optimal package found by the IP solver.

The branch and cut algorithm combines the concepts of branching and cutting planes to systematically explore the solution space and find the optimal solution (FORREST *et al.*, 2020). By interactively refining the relaxation and updating bounds, it progressively narrows down the search and improves the quality of solutions.

The branch-and-cut technique may be considered as an extension of the branch-and-bound approach as a conceptual framework. In essence, this approach expands upon the existing branch-and-bound framework by incorporating supplementary cuts that are created and applied to each node of the branch-and-bound tree, before the pruning and branching procedures. An algorithm of branch-and-cut method is described in the study of Chen D.S. and Dang (2009).

The *First-Fit Decreasing (FFD)* algorithm, was investigated by Johnson (1973) in his doctoral thesis, with the main result being a proof that the *FFD* for the bin packing problem never returns a solution that uses no more than ($11/9 times OPT$) bins, where OPT is the optimal number of bins. Later, Johnson and Garey (1985) propose a new version that returns a solution that uses no more than ($71/60 \times OPT$) bins. These discoveries permit to classify *FFD* as an approximation algorithm instead of a heuristic.

The *FFD* was first used in the classical problem of one-dimensional packing that is to minimize the number of bins used to pack the items. This problem is applicable to several areas that can varies from the stock-cutting problem to the inclusion of television commercials into station program´ breaks (JOHNSON; GAREY, 1985).

2.6 Relevant Studies

2.6.1 Maintenance Optimization Studies

The objective of maintenance optimization studies is to minimize overall system costs while simultaneously enhancing system availability through the implementation of optimal maintenance policies and inspection intervals. According to Sharma *et al.* (2011), previous studies mostly focused on optimizing the system maintenance cost rate while neglecting other system performance measures.

The maintenance plan (PM) aims to assure safe system operation and availability by reducing the probability of unpredictable failures (SMITH; HINCHCLIFFE, 2003). Grida *et al.* (2017) and Sharma *et al.* (2011) stated that the optimization model for PM can focus on the performance of costs, availability, or both. This is in line with Smith and Hinchcliffe (2003), since the system unavailability may increase the production losses.

Although it can occur at any phase of the product lifecycle, the optimization analysis is more effective if carried out as early as possible in the start of a new project. According to Blanchard (2004) and Abrahão *et al.* (2019), without a focus on the dependability aspects from the start of the system design, several logistical support problems will occur, impacting the system performance and costs.

The optimization of maintenance and logistics issues has emerged as a significant area of interest among researchers and professionals in the aerospace sector. The following studies pertain to maintenance optimization and encompass the utilization of various models and methodologies that are employed based on the specific attributes of the application and the problem under consideration.

The studies of aircraft maintenance optimization have been approached in different segments and manners by authors:

2.6.2 Task Interval Definition

The articles in this part bring maintenance optimization investigation that aims to optimize the repeat interval of one task or a set of tasks in a system.

The study conducted by Ahmadi and Kumar (2011) examined the optimization of individual item task and interval. Ahmadi proposed a Cost Rate Function (CRF) to determine the most effective maintenance strategy for an aircraft component that exhibits aging behavior. The study also took into account the presence of a hidden failure, as analyzed by the MSG-3 Failure Effect Category (FEC) analysis. In this specific situation, a task is mandatory if its failure has the capacity to jeopardize safety, and there are three alternatives available: implementing a standalone Failure Finding Inspection (FFI), executing a standalone restoration (RST) task, or utilizing a combination strategy comprising both FFI and RST activities.

The authors employed the Mean Fractional Dead Time ($MFDT$) concept to determine the average proportion of time that the item is in the failed condition during the period between inspections. The model takes into account the cost of multiple failure in function of the cost of an accident, the average unavailability ($MFDT$) and the rate of demand of the hidden function. These parameters are components of the cost rate function (CRF) and impact the specific costs associated with the system's lack of capability. In addition, the expenses associated with scheduled and corrective maintenance activities are also considered in the CRF. The most efficient maintenance strategy is determined via the use of analytical analysis and graphical outcomes.

The $MFDT$ concept was previously employed in the gas sector by Rausand and Vatn (1998) to develop a maintenance plan for a surface controlled subsurface safety valve

(*SCSSV*) used in offshore oil and gas installations.

It is noteworthy that the MSG-3 methodology permits the combination of tasks exclusively in cases when the failure outcome is classified as *evident safety* or *hidden safety*. Ahmadi *et al.* (2010) proposes in his thesis that the combination of tasks should also be employed in the context of the hidden/non-safety category. In cases where the failure is not associated with safety considerations, the MSG-3 analyst often ceases the task definition (level 2) analysis promptly upon identifying a suitable and efficient maintenance requirement. This MSG-3 recommendation has two objectives, first is to force the analysts to evaluate all possible maintenance strategy to avoid a redesign in case of safety categories, and the second is to establish only the minimum number of requirements to keep the cost at minimum.

The problem of defining a better interval for a *FFI* was further examined byLienhardt *et al.* (2012) employing Semi-Markov process to calculate the steady-steady availability of the system in function of the preventive maintenance interval. The researchers consider the rate of demand for the hidden function as a non-homogeneous poisson process and derive equations that enable the calculation of the joint probability of both primary and backup system failures. They define an optimization model as function of the task interval wherein the objective is to determine *FFI* interval that minimizes the overall costs while maintaining the level of corrective maintenance within an acceptable range. The authors employed a non-linear programming method to determine the optimal FFI interval. The model was subjected to testing using a pressure relief valve, commonly used in the pressurization system of Airbus aircraft. The results of the study indicate a distinct presence of an optimal time period that reduces the probability of complete system failure.

These two studies bring important contribution for definition of the *FFI* interval. A failure finding task aims to avoid the occurrence of multiple failures within a defined period. The joint probability required and the demand rate for the hidden function helps define maximum exposure time and task interval. The *MFDT* and Markov process concepts demonstrated to be useful tools to calculate the time which the hidden function is unavailable for items subject to aging and items with constant failure rate respectively. Nevertheless, the strategy proposed in both research takes into account the interval for a single item as demanded by the MSG-3 analysis at *MSI* level. They do not consider the relationship with other tasks at the system level to determine an optimal system performance.

The problem of establishing maintenance intervals for a set of system tasks was also investigated by Deschamps and cattel (2014). The authors describe the definition of intervals for a set of four activities related to a mechanical system that experiences major failures. The authors suggest time periods for a group of four scheduled maintenance activities, taking into account the cost of maintenance and the constraints revealed by fault tree analysis while assessing the safety of the system.

The optimization model presented by MATA FILHO and Abrahão (2020) also addresses an issue analogous to the one discussed by Deschamps and cattel (2014). The authors integrated the assessment of failure probability into their model, so taking into account its influence on safety margin and total expenses. The optimization method included not only the costs of preventative maintenance, but also the failure characteristics of the components, the charges related to corrective actions, the system fault logic, and the effects of failure on safety margins. An objective function for cost minimization was developed, taking into account the constraints imposed by interval range limitations and the tolerable probability of system failure. The optimization problem was tackled by testing the Tabu-Search, Black Hole, and Simulated Annealing meta-heuristics. All methods successfully identified a sub-optimal alternative within a reasonable time frame.

In their study, Bozoudis *et al.* (2018) introduced an optimization tool to define a maintenance plan of a fuel pump system composed of two subsystems and five components. The tool takes into account the system reliability function, minimal cut-set, improvement importance associated with each component, costs of scheduled and non-scheduled maintenance. In addition to the aforementioned points, the model takes into consideration the life cycle of the system and the reliability distribution of its constituent parts. The study discusses the financial implications of preventive and corrective maintenance, as well as the cost associated with replacing all components simultaneously. Additionally, it consider the confidence level of in successfully finding a spare part required for maintenance activities. The cost-adjusted improvement importance is used as factors for scheduled maintenance optimization and the spare parts estimation.

The studies conducted by Deschamps and cattel (2014) and MATA FILHO and Abrahão (2020) made a valuable contribution by including maintenance cost optimization with the restrictions derived from Fault Tree Analysis (FTA). They focused on defining intervals for a set of tasks while assessing the influence of these intervals on the system's safety margin. Furthermore, the research conducted by MATA FILHO and Abrahão (2020) introduced the concept of assessing the expenses associated with corrective actions throughout the life cycle of the system. The method presented by Bozoudis *et al.* (2018) adds the concepts of importance metrics for each component, and the confidence level of spare part stock in the optimization of maintenance plan for a set of tasks.

2.6.3 Maintenance Planning Optimization

The following studies utilize data from operators' approved maintenance plan *OAMP* information to optimize the Aircraft Maintenance Planning, labeled as *AMP* or the Flight and Maintenance Planning, named as *FMP* for both civilian and military fleets. It is important to mention that the development of *OAMP* is based on the maintenance requirements provided by the aircraft manufacturer in the Maintenance Planning Data (*MPD*) document. The Task Allocation and Packing Problem solution, introduced in this thesis, provides a customized maintenance plan that may be utilized as inputs for these investigations.

The research study by Abrahão and Gualda (2006) discussed the issue of improving fleet preventive maintenance planning, taking into account different operational and maintenance resource limitations. The decision-making process entails considering variables such as flight scheduling, remaining aircraft operational time, and the accessibility of the maintenance facility. This enables the identification of the optimal timing and choice of the aircraft to be taken out of operation and sent for maintenance. The problem is resolved by employing the hybrid ant colony optimization (*ACO*) meta-heuristic as the fundamental method. The authors assert that the solution method yielded favorable outcomes in the experiments conducted on a fleet of 20 aircraft. The objective function was formulated to maximize many cost considerations related to aircraft utilization and remaining flight time, as well as hangar space constraints, while taking into account the impact on availability for two separate squadrons.

In their study, Gavranis and Kozanidis (2015) formulated a problem known as the Flight and Maintenance Plan (*FMP*) and developed an accurate algorithm to address it. The algorithm is designed to determine the optimal allocation of available aircraft for flight operations, considering factors such as flight duration and aircraft maintenance remaining due time for maintenance. The primary goal is to maximize the availability of the unit fleet within a specified planning period. The test model considers various factors, including the quantity of aircraft, the flight load in the period, and the utilization for each time period. Additionally, it accounts for the availability of maintenance station resources, time and dock space, as well as the residual flight time for aircraft leaving maintenance and the residual maintenance time immediately after aircraft are taken out of service for maintenance. The model uses an objective function with the aim of maximizing the cumulative residual flight time availability of the unit across a defined planning period. This involves aggregating the individual aircraft time availability. The resolution method applies an exact solution algorithm that initially computes a valid upper bound on the optimum value and interactively decreases this bound until a solution that attends the restrictions is found.The algorithm under consideration was evaluated within a division of the Hellenic Air Force (HAF), and the authors noted that the proposed approach demonstrates enhanced effectiveness compared to the commercially accessible tools employed by many operators.

Shah *et al.* (2017) conducted a study that shares similarities with the previous FMP research in terms of optimizing the aircraft maintenance plan (*AMP*) for a military fleet consisting of seven Sukhoi aircraft. The case is formulated as an optimization problem aimed at enhancing fleet readiness through the allocation of aircraft to maintenance activities, employing a multi-integer linear programming (*MIP*) approach. The (*AMP*) optimization model takes into account several key factors, including the fleet size, the operational time horizon, the limits imposed by hangar resources, which can accommodate up to three aircraft at a time, the interval between inspections, and the remaining hours of each individual aircraft. Consequently, the model is designed to optimize the quantity of aircraft available in order to achieve the highest level of operational readiness.

The subject of (*FMP*) for military aircraft was also been addressed in recent studies conducted by Balakrishnan *et al.* (2021). The researchers employed two types of meta-heuristics, namely the Genetic Algorithm (GA) and a modified Honey Bee algorithm, in order to strategize fleet usage and maintenance stoppages with the objective of optimizing the aircraft utilization rate (*UR*). The researchers devised a computational framework employing a modified honey bee meta-heuristic algorithm, which was subsequently applied to a fleet consisting of eight aircraft. The planning period of 360 days was taken into consideration, along with determining the minimum number of aircraft in operation, establishing the maximum number of flight hours per year, and setting a minimum threshold for the number of flying hours per aircraft in a given month. The researchers conducted a comparative analysis of the performance of the meta-heuristics, and determined that the modified honey bee algorithm exhibited superior outcomes.

In their study, Deng *et al.* (2021) developed a Decision Support System (DSS) with the goal of improving the maintenance check schedule. The *AMP* framework assigns maintenance tasks during inspections and includes a module for scheduling maintenance shifts. At first, an algorithm analyzes the specific time frame specified by the user for each inspection category (A-Check, C-check, D-check), as well as the capacity of repair facilities to accommodate the number of aircraft. Next, those times are subdivided into distinct intervals that are regarded as bins. A heuristic algorithm allocates the check activities to appropriate bins, taking into account the available hangar resources, the frequency of tasks, and the necessity of completing them. Ultimately, the DSS organizes the maintenance shifts by considering the necessary maintenance for each check and the resources needed. The DSS is an AMP software developed using the Python programming language and transformed into an executable file with a user-friendly graphical interface. The validation tests were conducted using data from 51 Airbus aircraft currently operational at a prominent European airline.

The aforementioned studies focus on AMP (aircraft maintenance planning) and FMP (flight and maintenance planning) challenges. Their objective is to assist operators in making strategic decisions in the operating environment contributing to cost reduction and improvement on the availability. Basically, all models considers the fleet utilization, hangar maintenance resources and aircraft remaining hours. All of those studies contribute to this thesis by bringing aspects related to a fleet that can be considered in the task packaging problem (TAP) investigation.

2.6.4 Maintenance Packaging Optimization

The following studies are directly related to the task allocation problem (TAP) that is the subject of this thesis. They treat the aspects of packaging or de-packaging process to be used by the airlines to produce their approved maintenance program.

Muchiri *et al.* (2009) presented a model for grouping tasks into manageable packages that could be completed at extended maintenance intervals during base activities or within a specific time frame during line maintenance.The authors propose an initial interval de-escalation to permit the management of packages without exceeding the original limit stated on the OEM`s MPD. The model is capable of handling various operational scenarios and takes into account aircraft utilization based on season.The Maintenance Item Allocation Model (MIAM) simulates aircraft utilization, calculates the due maintenance activities in different scenarios, and allocates them in a cluster. The model is validated using the data collected from a European airline that operates both scheduled and unscheduled flights with Boeing 737 NG aircraft. Nevertheless, the author did not consider the effects of corrective maintenance and their impacts on the production losses.

Li *et al.* (2012) presented some aspects related to the optimization of maintenance work packages. These authors considered the equalization of a packaged A-check. The equalization process splits the A-check into several other smaller packages that can be accomplished at line maintenance overnight. This can avoid a peak in the maintenance resource utilization, but it requires more intensive control and management of maintenance. The study focused on testing the performance of algorithms but also highlighted some useful aspects of the airline maintenance scenario. To achieve an optimum de-packaging result, the algorithm evaluates the original maintenance in an interval of each task and recombines them into several new packages. Besides the task intervals, the algorithm considers the relationships of tasks being packaged, concerning the systems (ATA code), task type, and aircraft zones where the tasks are accomplished. However, it does not consider either the failure characteristics of components or the probability of unscheduled maintenance and its impacts on the flight network.

Holzel *et al.* (2012) present an investigation into an optimization applicable to maintenance packaging and task scheduling They use the single-task oriented approach and look for the period when the aircrat is on the ground to plan the task or tasks(clustering). They consider this problem NP-Hard and use a heuristic method to solve it. The solver considers the RUL of the item and the availability of resources and the aircraft on the ground to plan the maintenance. A penalty cost for wasted life is included in the formulation, but the probability of failure and its consequences are ignored in the study. Also, the economy due to the clustering of tasks is not considered.

Senturk and Ozkol (2018) also proposes de-packaging and single-task oriented control of some maintenance requirements related to A and C checks. The objective was to improve fleet availability by reducing the time the aircrafts are on the ground for maintenance purposes. They also suggest a software to support the re-inclusion of task in a package according aircraft usage. Basic aspects are considered in the model,such as, the resources required, maintenance task interval and usage parameters. The authors claims for gains of using the single-task concept proposed after the validation and comparison performed with data of an A320 fleet. Nevertheless, the probability of corrective maintenance and the gains due to the packaging effect are not considered.

Witteman *et al.* (2021): Propose a heuristic method for allocating maintenance tasks at specific time intervals known as bins. The goal is to assist operators in their daily maintenance planning activities in order to keep their fleet flying. They define the problem as a time-constrained variable-sized bin packing problem, with bins of varying sizes distributed along the time horizon. and regard it as an NP-Hard problem The authors emphasize the problem of allocating tasks based solely on engineers' experience. The authors also proposed a de-escalation to improve flexibility, but they added a cost based on the length of the de-escalation. As a result, the optimizer attempts to assign the most expensive tasks closer to the end of their useful lives. They consider the following properties that indicate task similarity: ATA code, interval, zone, and check type. They also mention that grouping similar tasks into a work package reduces the overall number of tasks. Nonetheless, the study does not take into account the likelihood of failure and the associated opportunity costs.

Lee *et al.* (2022) suggests the integration of remaining useful life (RUL) prognostics of a PHM capable system with a maintenance planning framework. It uses the information from RUL prognostics estimated by a Bayesian regression model to define the optimum opportunistic maintenance schedule for the brakes. The authors integrate the results of a prognostic tool using a mixed-linear integer programming(MIP) solver, considering the cost of scheduled and unscheduled replacement. The solver also evaluates the maintenance slot and hangar availability. Due to the specific characteristics of the problem, they do not use the possibility of packaging the brake tasks with the tasks from the landing gear system that would share the same preparation activities. Another point is that PHM would be integrated with a learning mechanism as mentioned by (OCHELLA *et al.*, 2022).

Si *et al.* (2023) also suggests strategies for allocating tasks in maintenance packages. First, the executable interval is established, which is a time period in which the task can be assigned. For this, the maintenance cost parameters, failure characteristics, and a pre-determined risk value defined by the operators based on their assessment of the failure relevance are taken into account. The best package to include the task is then determined based on the overlapping of executable intervals, correlation between tasks, and package limits. The cost rate is determined by the projected cost of loss of unit uptime and the average time of aircraft operation. The study highlights interesting topics such as the acceptable level of corrective maintenance that users can endure, as well as the possibility of expanding the interval limitations based on task importance. Nonetheless, the study does not consider the operational profile, the advantages associated with the combination of activities that share the same preparation tasks, nor the zone and skilled resource constraint.

Silva *et al.* (2023) proposed the implementation of a maintenance scheduling framework with the use of two algorithms. The static algorithm produces the initial plan and, an adaptive algorithm that utilizes the reinforcement learning mechanism to update the initial scheduling of maintenance tasks. The algorithm for optimization utilizes three key performance indicators: time slack, which measures the time difference from the due date; ground time, which quantifies the duration that the aircraft is not in flight; and change score, which evaluates the extent of deviations from the original maintenance plan. The static algorithm employs the flight plan, checks schedule, and average fleet utilization to generate a maintenance plan. It allocates individual tasks to maintenance checks or smaller maintenance slots in order to minimize the downtime. The adaptive algorithm receives the flight plan for the fleet and the scheduled tasks, which are generated by simulating new faults and predicting the remaining useful life (RUL). This algorithm builds upon the current maintenance plan, only making the necessary modifications instead of creating an entirely new plan each time.

2.6.4.1 Summary

The task allocation research can be summarized by examining their objectives, methodologies, and the features considered by each author.

Objectives

Muchiri *et al.* (2009), Li *et al.* (2012), Lee *et al.* (2022), and Si *et al.* (2023) concentrate on minimizing costs, whereas Holzel *et al.* (2012), Senturk and Ozkol (2018), and Silva *et al.* (2023) prioritize maximizing fleet availability. The study conducted by Witteman *et al.* (2021) examines the dual objectives of minimizing costs and maximizing availability.

Optimization Methods

Lee *et al.* (2022) and Si *et al.* (2023) solution was found using an Integer Programming algorithm. Heuristic algorithm was used by Holzel *et al.* (2012); Li *et al.* (2012), Witteman *et al.* (2021), and Silva *et al.* (2023). Lee *et al.* (2022) also used a regression model to estimate the remaining useful life of components. Simulation methods was used by Muchiri *et al.* (2009) and Senturk and Ozkol (2018).

Features

The probability of corrective maintenance is considered by Si *et al.* (2023), and indirectly addressed by Lee *et al.* (2022). The opportunity cost is addressed by Si *et al.* (2023) considering this cost as part of loss in aircraft uptime, and indirectly by Holzel *et al.* (2012) as they look for the opportunity of aircraft is on the ground to allocate a task or cluster of tasks. The operational and maintenance profile are used by Muchiri *et al.* (2009) which evaluate several operational scenarios and opportunities in the base or line maintenance activities to plan the packed tasks execution, and by Senturk and Ozkol (2018) and Lee *et al.* (2022) by looking for an opportunity to accomplish the tasks. Zone limits are considered in the studies of Si *et al.* (2023). Li *et al.* (2012) consider the zones as a parameter to define the correlation between tasks.

Table 2.6 presents a comparison of the features included by the authors in each Task Allocating problem study, and position the work in thesis within these researches. It was compiled only the studies that covers, even partially, aspects related to the maintenance task packing.

TABLE 2.6 – Literature, solution methods and features

	Objectives		**Methods**		**Features**						
Approach by	**Min. Cost**	**Max. Avail**	**IP**	**Heu**	**Life phase**	**Opp. Cost**	**CM Cost**	**Packing gain**	**Fleet profile**	**Zones Limit**	**Resources**
(MUCHIRI *et al.*, 2009)	■	.	.	⊡	*O*	.	.	⊡	■	.	.
(HOLZEL *et al.*, 2012)	⊡	■	.	■	*O*	⊡	.	.	.	.	■
(LI *et al.*, 2012)	■	.	.	■	*O*	.	.	⊡	⊡	⊡	.
(SENTURK; OZKOL, 2018)	⊡	■	.	⊡	*O*	.	.	.	.		■
(WITTEMAN *et al.*, 2021)	■	■	.	■	*O*	.	.	⊡	.	.	.
(LEE *et al.*, 2022)	■	.	■	⊡	*O*	.	⊡	⊡	⊡	.	.
(SI *et al.*, 2023)	■	.	■	.	*O*	⊡	■	.	.	.	.
(SILVA *et al.*, 2023)	.	■	.	■	*O*	⊡	.	.	⊡	.	⊡
This work	■	■	■	⊡	$D + O$	■	■	■	■	■	■

■ completely ⊡ partially *O* operational *D* development

IP Integer programming **Heu** Heuristics

Min Cost Minimize Cost **Max Avail** Maximize Availability

Opp Cost Opportunity Cost **CM Cost** Corrective Cost

It can be noticed that only Witteman *et al.* (2021) and Senturk and Ozkol (2018), partially, consider the optimization of both cost and availability. The model in this thesis operates in two ways to minimize expenses while increasing availability. The cost ratio goal function is first minimized using an *branch and cut* approach, and the maintenance stoppage downtime is then optimized utilizing the *FFD* concept.

The approach used to solve the packing problem can vary according on the model´s specification, the study´s purpose, and the project variables examined. Although heuristics and metaheuristics might identify good solutions to problems in a reasonable amount of time, linear programming approaches always deliver the best solutions to a given problem. In the thesis, an exact strategy was employed to offer an optimal solution to the packing problem with 787 items in a reasonable time. Besides this work, only (LEE *et al.*, 2022) and (SI *et al.*, 2023) use the integer programming to resolve the problem.

All the studies focuses on the operation and service phase of the life cycle. This feature is taken into account in this work and by Si *et al.* (2023) and partially adressed by Lee *et al.* (2022) since they use the Prognostic and Health Monitoring information for decision on packing.

The opportunity cost is addressed in this thesis as a parcel of cost related to the aircraft unavailability. Also, Si *et al.* (2023) considers this cost as part of loss of aircraft uptime, and Holzel *et al.* (2012) also consider indirectly this feature as they look for the opportunity of aircraft is on the ground to allocate a task or cluster of task.

The operational profile is other fundamental features to elaborate the maintenance plan that fits the operator´s real world. The study of Muchiri *et al.* (2009) evaluate several operational scenarios and opportunities in the base or line maintenance activities to plan the packed tasks execution. Senturk and Ozkol (2018) and Lee *et al.* (2022) adopted a similar approach in their work, by looking for an opportunity to accomplished the tasks.

Besides the available resources, the zone limits are considered in this thesis to support the task sequencing optimization. Si *et al.* (2023) and Li *et al.* (2012) address indirectly the zone when they consider some correlation between tasks.

2.7 Problem Specification and Analysis

This research focuses on the problem of task allocation in packages (packaging process in Figure 1.1) that occurs after the definition of maintenance requirements by the certification and MRB processes to generate the final maintenance plan used by the operator to maintain its aircraft fleet.

The main problem that affects the maintenance development is the gaps found in the process of developing maintenance plans, such as the absence of an efficient model and tools, which present suboptimalities or inconsistencies to obtain the best cost-benefit ratio. Also, immaturity of important parameters and absence of continuous follow-up of them contributes to worsen the resulting maintenance plan impacting the supportability performance.

As seen in the literature review and in the industry process, preventive maintenance labor, access data, and preparation tasks are normally considered in the packing process. However, costs of corrective actions due to the likelihood of failures, production losses, and savings resulting from maintenance task packing, are not systematically included in the optimization problem. It is important to mention that the latter parameters are not correctly addressed in any of the previous phases of the task interval definition.

Investigating the possibility of including those parcels of costs and savings, and integration with proactive data monitoring process, during the aircraft development and operation stages, is an important strategy to consider in the maintenance optimization studies.

The problem consists in allocating the maintenance requirements that came from the certification and MSG-3 analysis, in packages to be accomplished at each planned aircraft stoppage for maintenance. The goal is to define the best allocations for task t_j into the existent packages S, as shown in the Figure 2.13, to minimize costs.

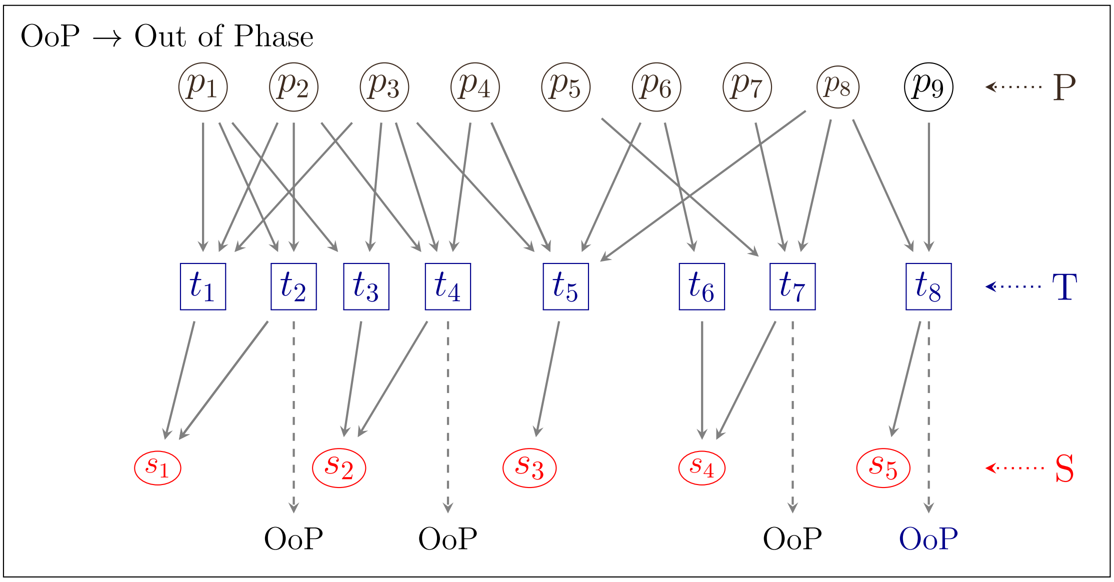

FIGURE 2.13 – Task Allocation Problem - TAP

These requirements have their limits defined in different intervals and usage parameters. The usage parameters are flight hours(FH), flight cycles (FC), Landings (LD), months (MO), equipment hours, such as engine hours (EH) or cycle(EC)

It is also important to group tasks as much as possible to increase availability. Although task packing is desirable, some tasks are expected bo be planned as *Out Of Phase* (OOP), out of a regular work package.

The task allocating and Packing problem depicted in the Figure 2.13 is summarized as follows:

Let $T = \{t_1, t_2, t_3, ..., t_{|T|}\}$ be a set of maintenance tasks, where each task t_j must be acomplished as near as possible to its limit interval lim_j and requires a quantity of man-hours and material mat_j and, a set of of preparation tasks.

Let $S = \{s_1, s_2, s_3, ..., s_{|S|}\}$ be a set of maintenance maintenance packages planned to occur at interval s_i. Depending on the planner´s decision, each package S_i will contain one or more of the tasks t_j. The task t_j interval lim_j, to be included in package s_i, must be greater than the package planned stoppage interval $stop_i$).

Let $P = \{p_1, p_2, p_3, ..., p_{|P|}\}$ be a set of maintenance preparation tasks [2]. The preparation p_k can be shared to one or more maintenance tasks t_j when he tasks are allocated in the same package s_i. Each preparation task p_k also requires a certain quantity of man-hours, mh_k and material, mat_k

The goal is to define the best allocation package s_i for each task t_j, as shown in the Figure 2.13 in order to reduce costs and downtime while increasing profitability.

2.7.1 Proposal of this study

The proposal of this research is to develop and test a new method to efficiently solve the TAP problem by considering all essential aspects and parameters to produce a optimum maintenance plan that can contribute to improve the effectiveness of maintenance plan since the start of operation and be able to assist operators in their short and medium-term maintenance planning.

Through the utilization of the proposed model, it is expected to: obtain gains in the total maintenance costs keeping the same safety operating level (H1); improve the availability of aircraft after optimization (H2); and provide resilience by exploring historical data acquired during product development and operation(H3).

It is expected that this will ensure a better maturity of the logistical support elements that are affected by the maintenance at the beginning of the operation phase, thus avoiding losses that are normally discovered and corrected only after years of operation.

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[2] In this work, a preparation task includes the initial aircraft set up, such as gain of access, energization, towing, etc., necessary to accomplish a maintenance task. It also includes the follow-on activities to be performed to finish the task execution

2.8 Conclusion

This Chapter presented an overview of the key theories and concepts that used in the thesis and a revision of the primary findings of past maintenance optimization studies and discusses the gaps and limitations of them. Finally, it was presented a general specification of the TAP that will be detailed in next Chapter.

In the Chapter 3 it will be presented the proposed method and its application in solving the problem. It will also cover the problem modeling, data and tools.

3 Method

3.1 Introduction

The preceding Chapter provides a review of prior studies on maintenance optimization and highlights the gaps and limitations associated with them. An outline of the theories and principles utilized in this study was also provided.

This Chapter provides an overview of the research methodology used and how it was applied to create and evaluate the model for effectively solving the Task Allocation and Packing (*TAP*) problem. Furthermore, it addresses the problem modeling, data used, and tool implementation, as well as the tests conducted to verify the effectiveness of the method.

3.2 Methodology Approaches

In order to achieve the goals of this study, a comprehensive strategy was adopted, combining exploratory, descriptive, deductive, and quantitative approaches. The study framework and methods applied are depicted in the Figure 3.1. The numbering above each process refers to each step of the Section 3.3.

An exploratory research was conducted to identify prospective aircraft supportability challenges and situations in order to gain a more comprehensive understanding of the current concerns. A literature review was conducted focusing on maintenance, dependability, maintainability, optimization methods, and other relevant topics. The exploratory approach included the examination of aircraft technical material, aeronautical regulations, and also involved visits and interactive discussions with airlines, manufacturers, and MRO representatives. Moreover, attending logistics and operational research seminars has enhanced the knowledge.

Consultations with the supervisor and other professors were conducted to discuss the information acquired through the exploratory approach. These discussions were essential in formulating and refining the research questions and determining the study's purpose.

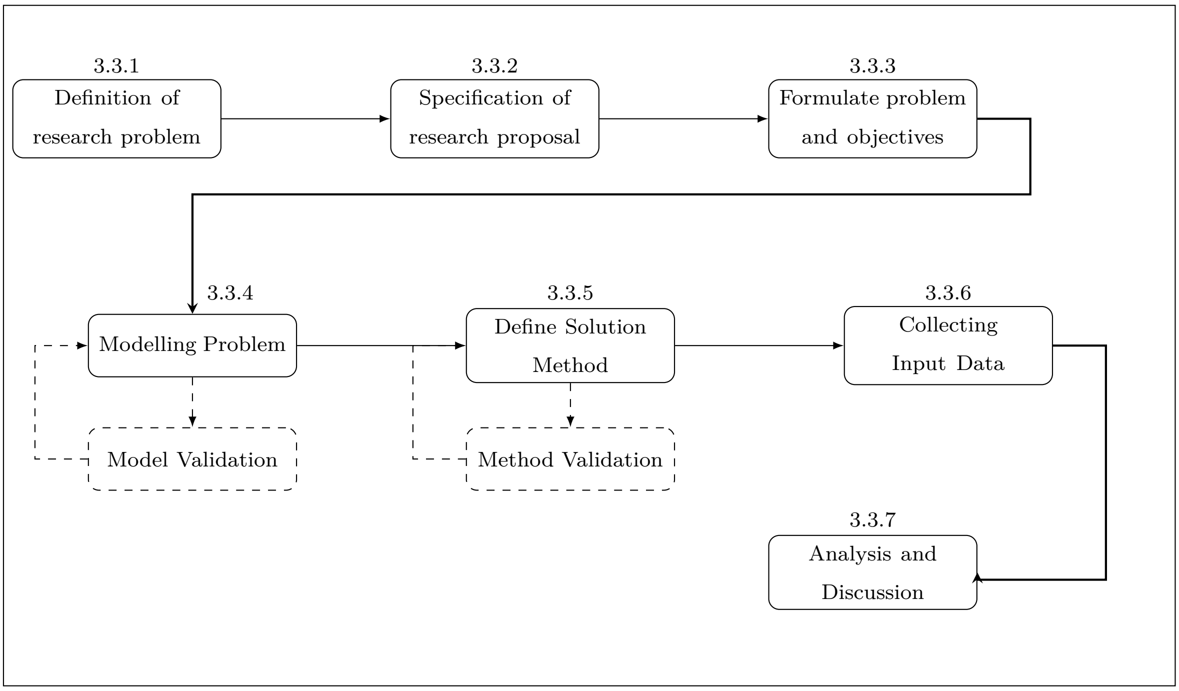

FIGURE 3.1 – Research Method Summary

The descriptive technique was employed to delineate the interfaces and data related to problem, the methodology for ascertaining the optimal task allocation, the factors relevant to determining the inclusion of a task in a package, and the procedure for organizing the tasks within a package. Additionally, it served to elucidate the framework and model to the users.

To validate the model with the supervisor and pairings, preliminary and final test data were analyzed using quantitative and deductive methodologies.

In order to delineate and investigate the subject matter, formulate hypotheses, and propose an optimization model for efficiently organizing tasks into bundles, a deductive methodology was utilized.

3.3 Methodology Application

This Section describes the study's research strategy for achieving the project's goal.

3.3.1 Definition of Research Problem

The research project proposal was formulated by integrating the insights gained from the literature review on supportability issues, past expertise in devising maintenance plans using the MSG-3 methodology, and consultations with the project supervisor and other experts in the field of integrated product support. The decision was made to focus the study specifically on the area of aircraft maintenance to identify any shortcomings in the process pertaining to the creation of the maintenance plan.

Finally, the problem was formulated in accordance with the specific need of aviation industry. In addition to doing a literature research, engaging in discussions, interviews, and consultations with experts in the maintenance development and planning, from a big brasilian manufacturer and airlines, provided the necessary support for taking the decisions. As a result, the research objectives are linked with the identified challenges and specified in accordance with the demands of aeronautical sector.

Literature review information were collected from different databases and scientific journals, as well as form consultation of books and thesis in the ITA library. Scientific papers on the subject were searched on different databases, such as Engineering village, IEEE, Elsevier, Science Directed, Spring, Emerald, by means of the ITA and CAPES sites using a set of keywords related to maintenance and optimization. For the literature organization it was used ReadCubePapers®, a commercially available tool, and the Start applications developded by Hernandes *et al.* (2012) from the Universidade Federal de Santa Catarina(*UFSC*).

3.3.2 Specification of Research Proposal

The problem definition was used as a basis to create the study proposal and establish precise objectives. The supervisor and specialists have agreed on the idea to explore and develop an optimization framework for solving the Task Allocating and Packing problem. This decision was made in light of the highlighted gaps, and in the research objectives of the AeroLogLab department.

3.3.3 Problem Formulation and Objectives

The TAP problem was formulated based on a deductive study of the scientific literature and the issues described by the practitioners from the aircraft industry. Initially, it was formulated three objectives , one related to the possible gains in cost [H1], other related to the improvement on the aircraft availability[H2] and the third regarding the possibility of updating the plan based on the learning from data acquired [H3]. After that, a first conceptual model, Figure 3.2 , was defined and presented to validation.

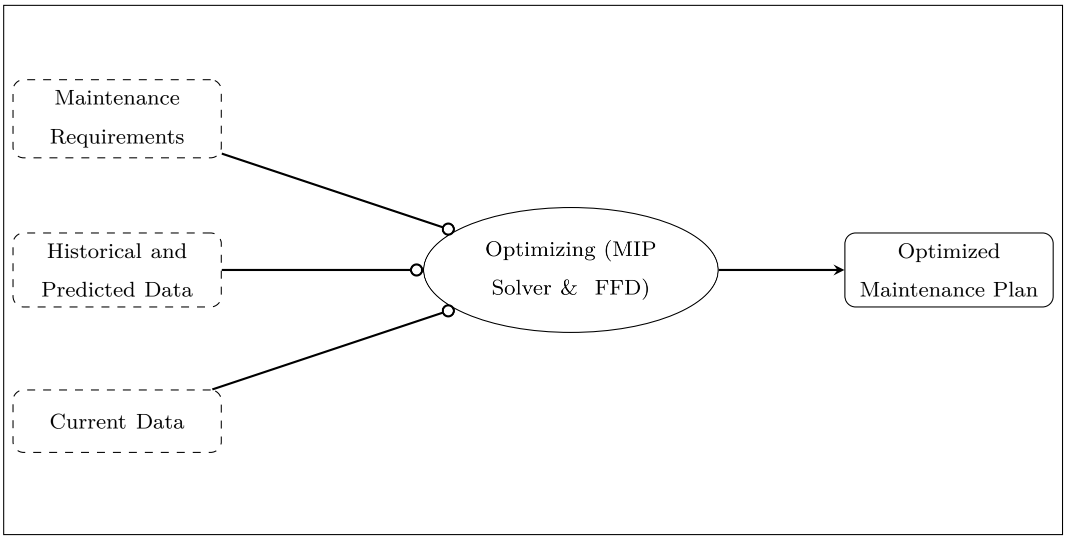

FIGURE 3.2 – Conceptual Model

3.3.4 Problem Modelling

The problem formulation follows a deductive and inductive approaches using the theoretical baseline and support from supervisor and others AeroLogLab´s professors. A preliminary model was designed considering the TAP problem as an operational research issue. Initially it was defined a cost rate function considering the basic maintenance data parameters and main cost factors, e.g the preventive cost, corrective cost and economy of packing together tasks that share some preparations. The model was validated with data from commercially available off-the-shelf components installed in a commercial aircraft. For each component task, it was considered the information of interval limits, the man-hours required, preparation tasks, the original allocation of tasks in packages, and the item failure rate. The components and data are listed in the Section 3.6 of this Chapter. The validation accounts on the comparison of costs between the proposed model outcomes and the original maintenance plan. The validation encompassed several tests as described in the Section 4.1

Following that, the model evolved to take into account additional elements such as the operator's flight profile, hourly opportunity cost, the availability of maintenance resources and the possibility of having *out-of-phase* tasks.

The model was also enhanced to improve aircraft availability by incorporating the concept of task execution sequence within the package as presented in the Figure 3.3. In this case, a bin packing optimization concept was employed. In addition, the packing savings calculation method was revised to expanding the optimization capability.

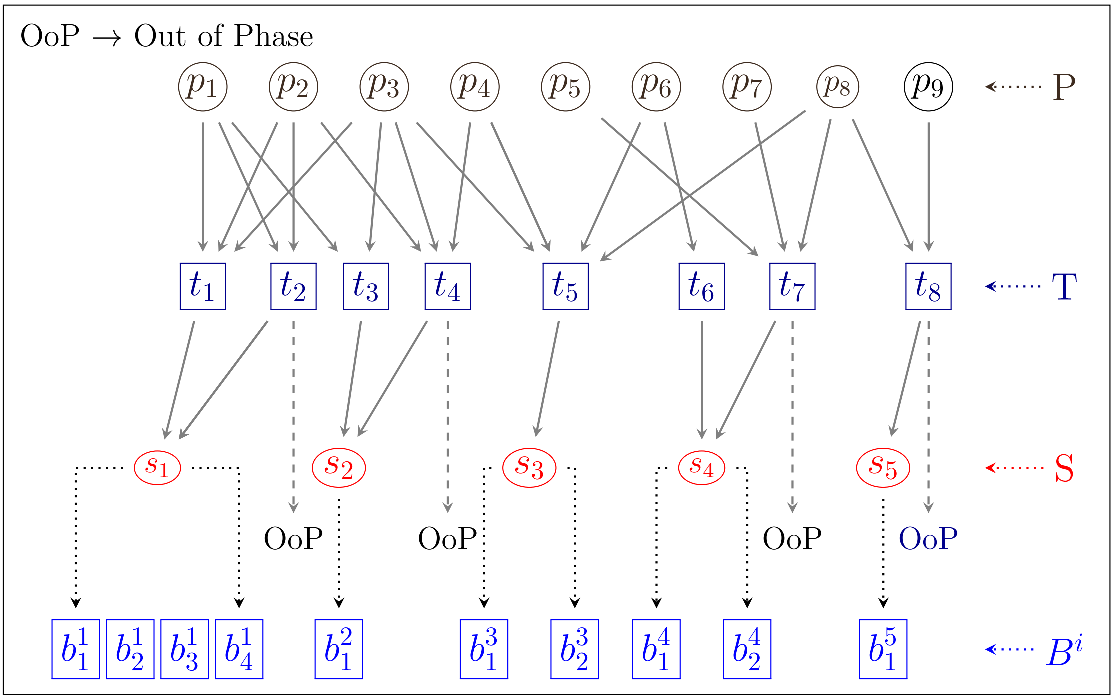

FIGURE 3.3 – Task Allocation & Packing Problem - TAPP

3.3.5 Selection of Solution Method

The solution method was defined following an exploratory study of the operational research concepts and tools used in the optimization problems. The studies included a review of the scientific literature concerning exact and heuristics methods,and also discussion with supervisor and specialists in the operational research and optimization areas.

The problem is resolved in two stages: initially, the solver efficiently assigns tasks to packages, ensuring that the component remains within its designated flight hour range and minimizing overall costs. Subsequently, for each work package, tasks are grouped using a *Bin Packing Problem* approach, where multidimensional tasks are arranged into multidimensional bins, with the aim of minimizing the total downtime of the bins. This paper focuses on the Task Allocation & Packing Problem (TAPP), which arises from the shift in the way the solver allocates tasks to packages by organizing them into time bins.

To the method created to solve the TAPP was named *ETAPPS (Efficient TAPP Solver)*. ETAPPS was tested by utilizing the maintenance records data of aeronautical components in 20 test instances, synthetically generated and based on statistical data from real maintenance records. The results os tests are detailed in the Chapter 4.1.

As all variables are expected to be integer and the constraints and objective function are linear, The TAPP is modeled as an Integer Linear Programming formulation. Thus, it was decided for the use of *branch-and-cut* and *First-Fit-Decreasing* algorithms that were capable of solving the problem in short period of time, attending the user´s perspective.

Details of the tools used in implementation of ETTAPS are described in the Subsection 3.4 of this Chapter.

The solution method includes additional algorithms to permit reading external with data to be used by the model, and writing external data with the optimization outputs.

3.3.6 Collecting Data

To collect data for the tests, an exploratory and quantitative method were used. Initially, historical maintenance data from a set of six components commonly seen on commercial aviation systems, that have been de-characterized to meet security needs, was chosen to conduct early testing and verify the model's sensitivity and coherence in terms of the resulting outcomes.

To check the robustness of the model, another set of 85 components generated synthetically based on data of real aeronautical components from general aviation, such as pumps, filters, control panels, starters, pressure switch, usually used on aircraft systems. Part of them with failure rate (λ) information available. For the remaining items the failure rate was estimated based on the study of Smith (2005) that suggested a range of failure rate based on the type of component. The Section 3.6 describes the details of the input data.

Using the information from those items, a total of 340 tasks were created, with 4 tasks assigned to each component. These tasks were then added to the current task set in order to proceed with the tests and verify the responsiveness and accuracy of the model.

At the start of a new product development, it is important to remember that certain required data may not be readily available. In such cases, it is necessary to reference standard handbooks, normative publications, and manuscripts that give methods for predicting the parameters. It is essential to verify this value during the development process. Furthermore, data on comparable items can be utilized, taking into account their similarity in terms of the operational environment.

In some preliminary tests the ML technique was used to predict component data from the results of previous run. These tests aimed to check the possibility to couple the optimizing solver with a learning module in order to improve the resilience of maintenance plan.

The last test of the model employed synthetic data based on real tasks from a commercial aircraft. Data de-characterization to protect product information had no effect on the model's suitability for real-world use. It was considered tasks from aircraft systems, structures and zonal program with intervals in flight hours, flight cycles and months.

3.3.7 Tests and Analysis

In order to carry out tests and verify the accuracy of the model, a combination of qualitative and quantitative methodologies were utilized. Multiple tests were performed using different combinations of components and situations to assess the effectiveness of the model and confirm the hypotheses. The results obtained via optimization were compared to those obtained without optimization, which replicate the outcomes attained by practitioners utilizing good engineering judgments.

The Chapter 4.1 provides a comprehensive analysis and evaluation of the tests, including an in-depth analysis of the details and outcomes. Further testing was conducted to verify the advantages generated by the First Fit Decreasing method for task sequencing. The optimal task sequence is determined by the amount of skilled resources needed, the constraints of the zone, and the relationship between tasks.

3.4 Tools

3.4.1 Solver

The model is implemented as a Mixed-Integer Programmimg (MIP) problem using Python 3 environment. MIP has emerged as a highly effective technique for modeling and solving real-world planning and scheduling issues, with almost limitless applications. (ACHTERBERG *et al.*, 2020)

The MIP solver used in this work was the Branch and Cut developed and maintained by (FORREST *et al.*, 2020) as well as Python 3, with the following libraries:

- numpy: (HARRIS *et al.*, 2020)
- pandas: (MCKINNEY *et al.*, 2010)

It is a very effective solution for resolving a number of Integer Programming problems, and it can also ensure optimality. This method is an exact algorithm made up of a *Branch and Bound* algorithm and a cutting plane method. (ALMGREN *et al.*, 2012) used the *Branch and Cut* framework with the *gurobi python* interface and noted a decrease in the number of *Branch and Bound* nodes and simplex iterations for most instance classes with time dependent costs. These authors work looks for determining optimal opportunistic maintenance schedules to foster a maximum replacement interval.

After optimizing the allocation of task in the packages, a second phase optimization process is initiated to pack efficiently the task in each package using the First-Fitting Decreasing (FFD) algorithm developed in Python language.

It is important to explain that complex systems' uptime is maximized by periodic maintenance tasks, which are normally grouped to minimize lifecycle costs. Maintenance packages are composed of tasks, and some tasks are grouped by common resources to make the package more efficient, minimizing cost and downtime.

3.5 Assumptions

1. Items are either subject to degradation exhibiting increasing in the failure rate (IFR), or not subject to degradation presenting a constant failure rate (CFR) behavior.

2. Components are subject to perfect maintenance and are considered as good as new (AGAN) after repair or restoration task.

3. Interval changes on degradation finding tasks (Inspections or Functional Checks) may require adjustments on measured parameters.

4. The task maximum interval limits, defined by the MSG-3 or certification processes, are considered a hard constraint in the model.

5. The interval of the first maintenance package is determined by selecting the shortest task limit among the components included in the test sample.

   NOTE: In some circumstances, this interval may be determined based on the marketing policies. In these cases, the items with interval lower than this limit will be considered as Out-of-phase (OOP).

6. The items are considered to be replaced in the event of failure during operation or during the preventive maintenance activities.

7. All tasks should be included in one of the pre-defined work packages or in an out-of-phase stoppage.

8. Limitations of the operator's resources such as man-hours and facilities are considered in the task packing optimization;

9. Task maintainability information are based on similar tasks from commercial aircraft; NOTE: In some test instances, it was included a variability in the labor allocated for each task for testing proposal.

10. Corrective maintenance labor is assumed to be three times more expensive than preventive maintenance labor.

11. The calculation of the maintenance downtime is based on the maintenance labor and considers the number of specialists required per task.

12. A task may seize a preparation, so its costs and time must be accounted only once per package. Savings for packing tasks based on the similarity between tasks as regarding the access and general tasks required to perform the tasks.

    NOTE:It is important to note that a preparation has the following attributes:

    name (Ex.: 141BL → in zone 141, open door BL), time duration in hours, material cost, and a subset of other preparations, if the preparation is a compound.

13. Loss of 70.000 USD per day is considered as the opportunity cost considering 8 flight hours a day, according to (SENTURK; OZKOL, 2018);

3.6 Input Data

1. Six commercial-off-the-shelf (COTS) components with known failure rates and maintenance data were chosen for the initial tests. These parts are used in the assembly of several aircraft on the market.

2. Another list with 85 aircraft components (C) were added to the tests. For 27 items all the information was available, including the failure rate (λ). For the remaining items, the failure rate parameters were estimated based on the study of Smith (2017)) that suggested a range of failure rate based on the type of component.

The maintenance task limits were estimated by randomly generating values within a uniform distribution ranging from 200 to 2400 flight hours (FH).

Additional missing parameters were estimated using the following approaches:

- limits for maintenance: estimated by randomly generating values within a uniform distribution ranging from 200 to 2400 flight hours (FH)
- man-hour: randomly generated considering an a normal distribution with average of 1.2 hours and variance of 1.0.

- material expenses: randomly selected within a uniform distribution ranging from 10 to 50 US$
- preparation or follow-on tasks: randomly selected from the preparation list.

The Table 3.1 presents a sample of the components:

TABLE 3.1 – Components List

Item	*Description*	λ	η	β	*lim*	*mat*	*mh*	*A*
$comp_1$	Starter generator	1.56E-04			1000	518.316	2.63	[2 3 5 12]
$comp_2$	Fuel Pump	7.74E-04			1500	387.319	3.28	[2 3 5 7 9 10]
$comp_3$	Main Battery	8.55E-04			300	564.245	2.71	[2 5 11 13]
$comp_4$	Ejection Pump	7.74E-04			1500	185.569	3.80	[2 3 5 7 8 14 15 17]
$comp_5$	Hydraulic pump	3.33E-05			4000	158.253	4.60	[2 3 5 13]
$comp_6$	Engine	1.00E-05			4800	152.667	11.06	[2 3 6 12 13]
$comp_7$	Hydraulic Check Valve	1.37E-05			1000	41.829	0.97	[4 10 1]
$comp_j$	...	...	...	... ...	...	...	...	[...]
$comp_{86}$	Spoiler Actuator	3.42E-05	...	...	1770	43,035	1.17	[15 9 13]

For each component is presented, the failure rate λ, the weibull-2P η and β, if available, the maximum interval limit for preventive maintenance lim, material cost mat, man-hour mh, and the set of preparation A with the data listed in Table 3.2.

TABLE 3.2 – Preparation List

Id	*Description*	*mh*	*mat*	$qualif_r$
1	Acft Energization	0.75		2
2	Safety Precaution	0.65		2
3	Acft Grounding	1.00		2
4	Faring Removal Installation	0.33		1
5	Follow-on Procedures	0.75		2
6	Engine Follow-on Procedures	1.00		3
7	Acft Jacking	0.87		2
k	...	...	...	...
662	561MT access panel	0.65	15	1

The preparations (prior or follow-on) for each item were generated randomly from the list of 19 preparations.

Based on these 85 items, it was synthetically generate more 340 tasks to continue the experiments.

After the first cycle of tests, historical records are generated for this work comprising: maintenance date; PM costs; man-hours spent; material consumed; operating hours; and failure probability.

Another indispensable concept is the opportunity cost (OC).(WIESER, 1984). OC represents the potential benefits that an individual, investor, or business misses out on when choosing one alternative over another. Concerning this work, OC represents the lack of profits or expenses due to maintenance stoppages.

The following constants were adopted in this work:

- $OCD = 70,000.00$, daily OC (USD), (SENTURK; OZKOL, 2018)
- $OHD = 8$, operating hours per day
- $HOC = \lfloor \frac{OCD}{OHD} \rfloor$, hourly OC
- $MHC = 70.00$, man-hour cost (USD)
- $CMCF = 3.0$, corrective maintenance man-hour cost factor.
- $CMTF = 1.2$, corrective maintenance time cost factor.

3.7 Formulation of the Optimization Problem

This Section provides the rules for any solution method to be adopted, a mathematical description of a system for maintenance planning. As all variables are expected to be integer and the constraints and objective function are linear, the TAPP is modelled as an Integer Linear Programming formulation.

Let $C = \{c_1, c_2, c_3, ..., c_{|C|}\}$ be a set of aircraft components indexed by t, with the following attributes each:

- $name_t$ (a defining name for component c_t);
- η_t (the Weibull characteristic life);
- β_t (the Weibull shape parameter);
- $usage_t$ (the usage parameter of component c_t);

A component may have some usage parameters: FH (if component is controlled by flight hour), FC (by flight cycles), MO (by months) or YR (by years).

Let $M = \{General,\ Airframe,\ Powerplant,\ Avionics\ \ Inspection\}$ be a set of aviation mechanics qualifications indexed by r to be allocated to task as needed, with the following attributes each:

- $qualif_r$ (technical qualification);
- $available_r$ (available mechanics for each technical qualification);
- $wage_r$ (wage for each qualification ($qualif_r$) expressed in US$/h).

Let $Z = \{z_1, z_2, z_3, ..., z_{|Z|}\}$ be a set of aircraft zones according to the ATA-100 Specification indexed by x, with the following attributes:

- id_x (zone z_x identifier);
- $major_x$ (1 if the zone is Major, 0 otherwise)
- $area_x$ (zone area); and
- $limit_x$ (the maximum number of people to remain simultaneously in the zone z_x).

Zones are designated physical areas of an aircraft that identify where maintenance activities occur.

Let $P = \{p_1, p_2, p_3, ..., p_{|P|}\}$ be a set of maintenance preparations tasks indexed by k, that must be performed before or after a maintenance task, to be efficiently allocated with the task to the set of packages, and not duplicated, as multiple task may use the same preparations.

Each preparation p_k has the following attributes:

- $name_k$ (a defining name for preparation);
- $cost_k$ (preparation p_k overall cost);
- mh_k (estimated preparation p_k man-hours);
- mat_k (estimated preparation p_k material expenses);
- $qualif_r$ (mechanic qualification needed);
- $qualif_k^r$ (numbers of mechanics for each qualification needed to execute the preparation task p_k);
- $type_k$ (a preparation **prep** or a follow-on **fo** task).
- $nmec_k$ (number of mechanics needed).
- dt_k (estimated preparation p_k downtime);

The cost for each preparation task p_k is calculated through Equation 3.1.

$$cost_k = \left[\sum_{r=1}^{|M|} mh_k^r \times wage^r + mat_k\right] + \left[\frac{mh_k}{nmec_k} \times HOC\right] \; for \; k \in \{1, 2, 3, \ldots, |P|\}. \quad (3.1)$$

Where, HOC is the hourly opportunity cost relative to losses in the revenue, mh_k is the number of man-hour required, and $nmec_k$ is the quantity o mechanics necessary to accomplish the preparation p_k.

Let $S = \{s_1, s_2, s_3, ..., s_{|S|}\}$ be a set of maintenance stoppages (or work packages) indexed by i, each with the attribute $stop_i$, the aircraft maintenance stoppage, and some other parameters to be updated after optimization: $cost_i$ (overall work package maintenance cost); dt_i (overall work package maintenance downtime); and $preps_i$ (the set of unique preparation tasks associated to the work package).

Let $O = \{o_1, o_2, o_3, ..., o_{|O|}\}$ be a set of *Out of Phase (OP)* stoppages, indexed by p, for some tasks that are anti-economical to fit in the preceding regular work package s_i. o_p stays between s_i and s_{i+1}.It can not be allocated to s_{i+1} because the component would fly after it's due flight hour limit.

Let $T = \{t_1, t_2, t_3, ..., t_{|T|}\}$ be a set of maintenance tasks indexed by j to be allocated to the one of the S packages.

Each task t_j, has the following attributes:

- cid_j (task related component identifier);
- lim_j (the flight time limit to accomplished task t_j).
- $last_j$ (the fight time of the last execution of task t_j)
- pmc_j (PM cost of t_j);
- $pmdt_j$ (PM downtime of t_j);
- $pmoc_j$ (PM opportunity cost associated to $pmdt_j$);
- cmc_j (CM cost associate to corrective maintenance of t_j);
- $cmdt_j$ (CM downtime associated to t_j);
- $cmoc_j$ (CM opportunity cost associated to $cmdt_j$);
- $ztime_j^{xr}$ (time required for each qualification m_r needed for task t_j to be executed in zone z_x);
- $znum_j^{xr}$ (number of mechanics of each qualification m_r needed for task t_j to be executed in zone z_x);
- $zone_j$ (aircraft zones where the task will be executed);
- $qualif_j$ (mechanic qualification needed);
- $nmec_j^r$ (number of mechanics of qualification (m_r) needed);
- $preps_j$ (list of preparations necessary to be accomplished prior or after task t_j);

A task t_j may be subject to certain constraints, as listed in the Table 3.3, if it is included in the same package as another task t_q. These constraints establish the relationship between the execution of tasks t_j and t_q.

TABLE 3.3 – Task Relationship Codes

Task	**Identification**	**Definition**
t_j	$afterStart_q$	end t_j after starting a relative task t_q
	$beforeEnd_q$	end t_j before ending a relative task t_q
	$afterEnd_q$	end t_j after a relative task t_q finishes
	$startAfter_q$	start t_j after a relative task t_q finishes
	$incompatible_q$	task t_j must not be executed at the same time of task t_q

This study applies the $startAfter_q$ that implies only start t_j after a relative task t_q finishes, and $incompatible_q$ implying that task t_j must not be executed at the same time of task t_q.

The reliability of a component c_t depends on the interval of the its stoppage for maintenance and is given by 3.2 or 3.3.

Equation 3.2 gives the reliability of component c_t included in task t_j planned to stoppage s_i occuring at each $stop_i$ interval:

$$R_t^i = \left[e^{-(\frac{stop_i}{\eta_t})^{\beta_t}} \right] \; for \; t \in \{1, 2, 3, \ldots |C|\} \;, \; for \; i \in \{1, 2, 3, \ldots |S|\} \tag{3.2}$$

The equation 3.3 gives the reliability of component c_t included in task t_j planned to out-of phase stoppage o_p occuring at each $stop_p$ interval:

$$R_p^i = \left[e^{-(\frac{stop_p}{\eta_t})^{\beta_t}} \right] \; for \; t \in \{1, 2, 3, \ldots |C|\} \;, \; for \; p \in \{1, 2, 3, \ldots |O|\} \tag{3.3}$$

The equations 3.4 and 3.5 below give the task t_j inherent preventive maintenance (PM) cost calculations:

The preventive maintenance cost related to labor and material for each task t_j is calculate through Equation 3.4.

$$pmc_j = \left[\sum_{r=1}^{|M|} mh_j^r \times wage^r + mat_j \right] \; for \; j \in \{1, 2, \ldots, |T| \;, \; for \; r \in \{1, 2, 3, \ldots, |M|\} \tag{3.4}$$

The preventive maintenance opportunity cost for each task t_j is calculated through Equation 3.5.

$$pmoc_j = \left[\sum_{r=1}^{|M|} \frac{mh_j^r}{nmec_j^r} \times HOC\right] \; for\ j \in \{1, 2, \ldots, |T|\} \;,\; for\ r \in \{1, 2, 3, \ldots, |M|\} \quad (3.5)$$

Expression $\left[\sum_{r=1}^{|M|} \frac{mh_j^r}{nmec_j^r}\right]$ represents the PM downtime $pmdt_j$.

The equations 3.6 and 3.7 below give the task t_j inherent corrective maintenance (CM) cost calculations:

The corrective maintenance labor and material cost for each task t_j is calculated through Equation 3.6.

$$cmc_j = \left[\sum_{r=1}^{|M|} mh_j^r \times CMCF \times wage^r + mat_j\right] \; for\ j \in \{1, 2, 3, \ldots, |T|\}$$
$$for\ r \in \{1, 2, 3 \ldots, |M|\} \quad (3.6)$$

The corrective maintenance opportunity cost for each task t_j is calculated through Equation 3.7.

$$cmoc_j = \left[\sum_{r=1}^{|M|} \frac{mh_j^r}{nmec_j^r} \times CMTF \times HOC\right] \; for\ j \in \{1, 2, 3, \ldots, |T|\},$$
$$for\ r \in \{1, 2, 3 \ldots, |M|\} \quad (3.7)$$

Where $CMCF$ is a cost factor for corrective maintenance that corresponds to the complexity of corrective maintenance in comparison to the preventive maintenance. $CMTF$ is the corrective maintenance time factor, which represents the increase in downtime caused by unexpected contingencies and unanticipated logistics demands, HOC is the hourly opportunity cost relative to revenue's losses, and mh_j^r is the number of man-hour of mechanics with qualification $qualif_r$ mechanic required, $wage^{qualif_r}$ is the man-hour cost of a mechanic with qualification $qualif_r$ required for task t_j.

The individual task executed as *out-of-phase* has the same inherent costs described by the equations 3.4 to 3.7.

The calculation of the overall maintenance cost of a *out-of-phase* stoppage O_p is similar to that one used for a standard work packages S_i except for the Estimation of the anticipated number of failures between two *out-of-phase* stoppages. O_p where the *out-of-phase* limit $stop_p$ is used instead of the package $stop_i$ interval.

Let A_j be a subset of P that contains the preparations tasks necessary to accomplish task t_j.

Let C_{ij} be a set of preparation tasks necessary to accomplish the task t_j whenever it is part of package s_i.

$$C_{ij} = \begin{cases} A_j & \text{if } x_{ij} = 1 \\ 0, & \text{if } x_{ij} = 0 \end{cases}$$

A task may seize preparations if it is included in a package, so its costs and time must be accounted only once per package s_i.

The total amount of preparations of package s_i is defined by the set P_i, and is calculated as shown in the 3.8:

$$P_i = \bigcup_{j=1}^{m} C_{ij} \tag{3.8}$$

Let $B^i = \{b^i_1, b^i_2, b^i_3, ..., b^i_{|B^i|}\}$ be a set of maintenance bins which are partitions of maintenance work packages (Figure 3.4). Each package is composed of subsets of tasks grouped by bins of concurrent tasks. These bins hold as many tasks as the number of mechanics of each qualification available or the limit of personnel for the task zone, whichever is less. If this number is exceeded, a new *Bin* must be used to hold other tasks for the same mechanics (or for the same zone) from the previous *Bin*.

As to the *Bin* downtime (dt^i_b), it may be accounted as the longest task and the overall bins downtime may be minimized by minimizing the number of bins.

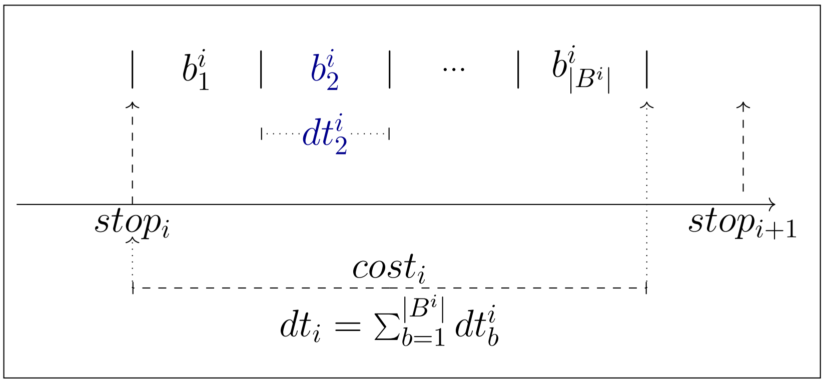

FIGURE 3.4 – Work package bins

Any resolution method to be used will output an optimal (or close to optimal) solution that expresses the allocations of tasks and their preparation to regular packages or to *"out-of-phase"* stoppages, and tasks in packages to bins.

It is defined 3 vectors of binary decision variables: (1) X_{ij}, to allocate task t_j and its preparations $preps_j$ to work package s_i; (2) O_{pj}, to allocate task t_j its preparations

$preps_j$, not included in the regular work packages, to out-of-phase stoppage o_p; (3) W_{jb} to allocate task t_j to bin b_b;

- The binary variables $X_{ij} = 1$ if task t_j is assigned to maintenance package s_i, and 0 otherwise.
- The binary variables $O_{pj} = 1$ if task t_j is assigned to an *out-of-phase* stoppage o_p, and 0 otherwise.
- The binary variables $W_{jb} = 1$ if task t_j is allocated to the bin b_b, and 0 otherwise.

Packaging tasks normally results in accomplishing some tasks before its due limits. The flight hour unused index is calculated using equations 3.9 and 3.10. This index is directly proportional to the number of flight hours that the task is anticipated when it is performed before reaching its flight limit.

$$unusedP_i^j = \lceil \frac{stop_i}{lim_j\ +\ last_j} \rceil - \frac{stop_i}{lim_j\ +\ last_j},\ for\ j \in \{1,2,3,...,|T|\}\ and\ for\ i \in \{1,2,3,...,|S|\} \tag{3.9}$$

$$unusedO_p^j = \lceil \frac{stop_p}{lim_j\ +\ last_j} \rceil - \frac{stop_p}{lim_j\ +\ last_j},\ for\ j \in \{1,2,3,...,|T|\}\ and\ for\ p \in \{1,2,3,...,|O|\} \tag{3.10}$$

The cost associated with the anticipation of a task is a fraction of the preventative cost of task t_j, and it is directly proportional to the unused indexes. f The equation 3.11 corresponds to the total preventive maintenance costs parcel related to task t_j, whenever it is included in the package s_i.

$$pmtc_j^i = \left[R_t^i \times (pmc_j + pmoc_j) \right] \tag{3.11}$$

The equation 3.12 corresponds to the expected total corrective maintenance costs if task t_j is included in the package s_i

$$cmtc_j^i = \left[\left(1 - R_t^i\right) \times (cmc_j + cmoc_j) \right] \tag{3.12}$$

The equation 3.13 corresponds to the *out-of-phase* stoppage total preventive maintenance cost.

$$pmtc_j^p = \left[R_t^p \times (pmc_j + pmoc_j) \right] \tag{3.13}$$

The equation 3.14 corresponds to the expected corrective total maintenance costs if task t_j is included in the *out-of-phase* stoppage O_p

$$cmtc_j^p = \Big[(1 - R_t^p) \times (cmc_j + cmoc_j)\Big] \tag{3.14}$$

The parcel related to the preparation cost is calculated considering that if task is included in a normal package together with tasks that share the same preparation activities, or if it executed as an out-of-phase task:

$$\begin{aligned} &\sum_{m=1}^{n(P_i)} prepc_m, \text{ for a normal work package } s_i \text{ or} \\ &\sum_{m=1}^{n(A_j)} prepc_m, \text{ for an out-of phase stoppage } o_p \end{aligned}$$

Where P_i is the set of unique preparation necessary for accomplishment of tasks included in the package s_i, and A_j is the set of preparation need for the out-of-phase task t_j

Equation 3.15 states the first Objective Function that minimizes the maintenance cost of all tasks $|T|$ and preparation $|P|$ in the defined horizon $|S|$.

$$\begin{aligned} Min\Bigg\{ &\sum_{i=1}^{|S|}\sum_{j=1}^{|T|} X_{ij} * \left[pmtc_j^i + \sum_{m=1}^{n(P_i)} prepc_m + cmtc_j^i + unusedP_i^j \times (pmc_j + pmoc_j)\right] \\ &+ \sum_{p=1}^{|O|}\sum_{j=1}^{|T|} O_{pj} * \left[pmtc_j^p + \sum_{m=1}^{n(A_j)} prepc_m + cmtc_j^p + unusedP_p^j \times (pmc_j + pmoc_j)\right]\Bigg\} \end{aligned} \tag{3.15}$$

Subject to:

$$X_{ij} \times unusedP_i^j >= 0, \ for \ j \in \{1,2,3,...,|T|\} \ and \ for \ i \in \{1,2,3,...,|S|\} \tag{3.16}$$

$$O_{pj} \times unusedO_p^j >= 0, \ for \ j \in \{1,2,3,...,|T|\} \ and \ for \ p \in \{1,2,3,...,|O|\} \tag{3.17}$$

Equations 3.16 and 3.17 hinder a task from having negative unused hours.

$$\sum_{i=1}^{|S|} X_{ij} * (lim_j + \ last_j) \geq \ \sum_{i=1}^{|S|} X_{ij} * stop_i, \ for \ j \in \{1, 2, ..., |T|\} and \ for \ i \in \{1, 2, .., |S|\} \tag{3.18}$$

$$\sum_{p=1}^{|O|} O_{pj} * (lim_j + \ last_j) \geq \ \sum_{p=1}^{|O|} O_{pj} * stop_p, \ for \ j \in \{1, 2, ..., |T|\} and \ for \ p \in \{1, 2, .., |O|\} \tag{3.19}$$

Equations 3.18 and 3.19 hinder a task from flying beyond its interval limit.

$$\sum_{i=1}^{|S|} X_{ij} + \sum_{p=1}^{|O|} O_{pj} >= \lfloor \frac{stop_{|S|}}{lim_j} \rfloor, \ for \ each \ j \in \{1, 2, ..., |T|\} \tag{3.20}$$

Equation 3.20 guarantees that the task t_j is executed at least $\lfloor \frac{stop_{|S|}}{lim_j} \rfloor$ times in planned horizon.

$$last_t = last_t \times (1 - X_{aj}) + stop_a \times X_{aj}, \ for \ each \ t \in \{1, 2, ..., |C|\} \tag{3.21}$$

For $i \in \{1, 2, ..., |S|\}, \ a \in \{1, 2, ..., i-1\}$, the last component stoppage is calculated (Equation 3.21).

$$\sum_{k=1}^{|P|} |P_i| = X_{ij} \tag{3.22}$$

For $i \in \{1, 2, ..., |S|\}, \ k \in \{1, 2, ..., |P|\}$, if the task is associated to the work package ($X_{ij} = 1$), the preparation p_k will be unique (Equation 3.22). It means that, the same door will not opened or closed more than once.

$$\sum_{r=1}^{|M|} \sum_{x=1}^{|Z|} X_{ij} \times znum_j^{xr} > 0, \ for \ each \ j \in \{1, 2, ..., |T|\} \tag{3.23}$$

For $x \in \{1, 2, ..., |Z|\}$ and $i \in \{1, 2, ..., |S|\}$, the number of mechanics of task zones must be greater than zero or the task will not be included (Equation 3.23).

The TAPP is solved at this point; tasks are associated with work packages, but their sequence and packing are not defined. So, a *Bin Packing Problem* will be solved by minimizing the number of bins through packing tasks as efficiently as possible.

$$minimize \ |B^i| \tag{3.24}$$

Equation 3.24 states the second Objective Function that minimizes the number of bins. This minimization also minimizes the overall downtime.

Subject to:

$$\sum_{b=1}^{|B^i|} W_{jb} = 1, \ for\ each\ j \in \{1, 2, ..., |T|\} \tag{3.25}$$

Each task must be in exactly one *Bin*, if it is associated to the *Bin* (3.25).

$$\sum_{j=1}^{|T|} \sum_{r=1}^{|M|} W_{jb} \times znum_j^{xr} <= limit_x \tag{3.26}$$

For each $b \in \{1, 2, ..., |B^i|\}$ and for each $x \in \{1, 2, ..., |Z|\}$, the number of mechanics cannot exceed the zone limit (Equation 3.26).

$$\sum_{j=1}^{|T|} \sum_{x=1}^{|Z|} W_{jb} \times znum_j^{xr} <= available_r \tag{3.27}$$

For each $b \in \{1, 2, ..., |B^i|\}$ and for each $r \in \{1, 2, ..., |M|\}$, the number of mechanics cannot exceed the available for each qualification (Equation 3.27).

$$W_{q,b} \times b < W_{j,b+1} \times b + 1, \ for\ b \in \{1, 2, 3, ..., |B^i|\}, \ for\ (j, q) \in \{1, 2, 3, ..., |T|\}. \tag{3.28}$$

Equation 3.28 guarantees that task j will be put in bin $b+1$, which is posterior to bin b because task j must start after q is finished ($j = StartAfter_q$).

$$X_{ij}^b = 1 - X_{iq}^b \tag{3.29}$$

For $j, q \in \{1, 2, ..., |T|\}$, $i \in \{1, 2, ..., |S|\}$, and $b \in \{1, 2, ..., |B^i|\}$; and for $j \in incompatible_q$ or $q \in incompatible_j$, as c and d are segregated tasks, Equation 3.29 guarantees that they will not be executed in the same bin.

3.8 Resolution Process Algorithms

The resolution strategy considered the use of an optimization by means of Efficient Task Allocation and Packing Problem Solver *ETTAPS* and the First-Fit Decreasing *FFD* algorithm for downtime optimization. In order to allocate tasks without optimization and considering only the utmost interval limits, simulating the process adopted in several programs, it was created an specific algorithm named *Simple*.

Figure 3.5 shows a general view the process and sequence of the algorithms used in this study. The algorithms details are presented in the Appendix A.

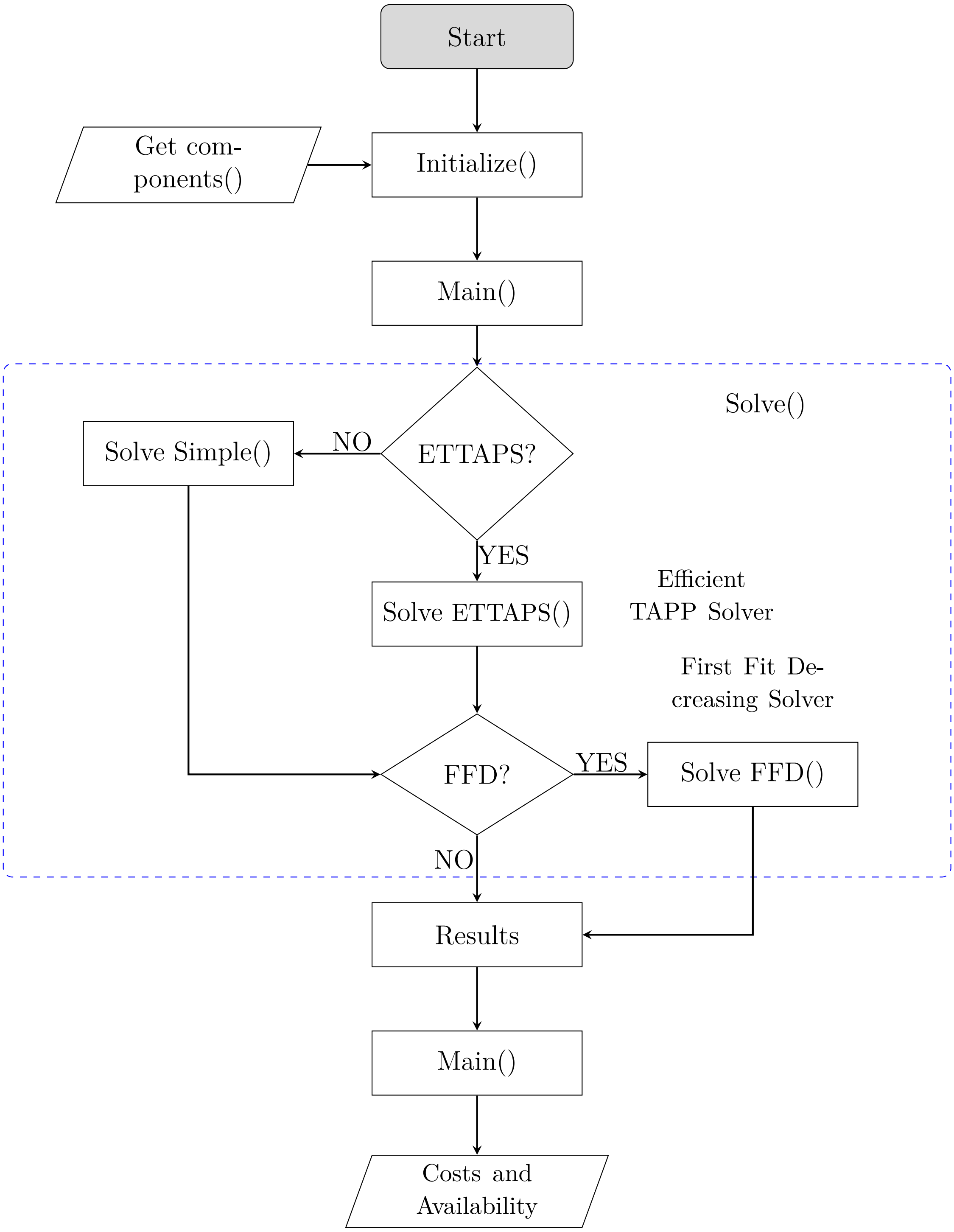

FIGURE 3.5 – Resolution Process

The *Initialize()* algorithm reads all external data related to components and tasks and initializes the optimization constants.

The *Main()* algorithm permits the choice of the solution method to be used, creates and calculates task parameters by using the *Create Task()* algorithm, and initializes the project variables.

The *Create Task()* algorithm utilizes external data gathered from components and tasks to establish cost parameters for the *Solve()* methods.

Depending on the method selected and specified in the *Main()* algorithm, the *Solve()* will allocate tasks using either the *Simple()* method or the *Solve ETTAPS()* optimization algorithm. The cost and downtime parameters are reset to zero and will be recalculated at the conclusion of the procedure.

The *Solve Simple()* routine only considers the task interval limit lim_j when allocating tasks, whereas the *Solve ETTAPS()* routine allocates tasks optimally using the *B*ranch and Cut algorithm, taking preventive and corrective maintenance costs, as well as costs of preparations, into account. If a task is assigned as part of a package with other tasks, the savings associated with allocating tasks that share the same preparation are accounted for. In contrast, if a task is designated as "Out of Phase" no cost savings are considered.

If set, after the *Solve ETTAPS()* optimization, the solver will use the *Solve FFD()* heuristic to reduce the total downtime.

The *Solve FFD()* heuristic utilizes the *First-Fit Decreasing* (FFD) algorithm to packing tasks within a package in an effort to decrease package downtime.

The *Main()* algorithm *Solve ()* results and presents the calculated Maintenance Costs (MC) and Availability (A) and, resulting task allocation at the conclusion of the process.

3.9 Conclusion

This Chapter explained the methodology employed in this study, as well as the math model and resolution strategy for the TAPP problem.

The results of the experiments undertaken to validate the model and corroborate the hypothesis will be presented in Chapter 4.

4 Results

4.1 Results and Discussion

The method utilized in this thesis was described in Chapter 3, together with the problem statement and math model. Also mentioned were resolution strategies , tools, and data.

The tests and their results will be described in this Chapter, with key elements and findings highlighted.

4.1.1 Initial Tests

4.1.1.1 Preliminary Tests for Model Validation

Initial tests were conducted to verify the validity of the proposed model. As specified in the Section 3.6, six commercially available components (COTS) were utilized in these tests and employed the LP simplex and Evolutionary solvers provided by Microsoft Excel™. Three distinct beginning setups were employed, namely: no initial allocation, original allocation, and the allocation proposed in the preceding iteration. The evolutionary solver demonstrated the capability to identify solutions regardless of the original configuration. The proposed model was validated by comparing the total cost provided by the original task allocation and the optimized allocation provided by the proposed by the solver.

Furthermore, a set of packages was created beforehand for the testing, which are based on the original tasks packaging distribution and component interval limit. Table 4.1 shows the packages created for the initial tests.

Also, for each task t_j it was added the man-hours relative to the set of preparation tasks A_j pertaining to the task. The total savings factor for items packaged in maintenance package s_i was given by α_i value calculated as follows:

$$\alpha_i = \frac{optimized_i}{nonoptimized_i} \tag{4.1}$$

TABLE 4.1 – Maintenance Packages Data

Package (S_i)	Interval ($stop_i$)	Occurrence in life (Q_i)
S_1	300	100
S_2	900	33
S_3	1500	20
S_4	3000	10
S_5	3900	7
S_6	4800	6

where, $optimized_i$ is the total cost of preventive maintenance of a certain maintenance package s_i after solver resolution and $nonoptimized_i$ is total cost of when considering the tasks allocated based only their maximum limit of interval lim_j without optimization.

The Tables 4.2 and 4.3 show the comparisons obtained for the initial case study. In the original allocation the total cost is higher than the the cost provided by the optimization model.

TABLE 4.2 – Original Maintenance Package Scenario

	Tasks Allocation						**Package Cost**	**Gain**
Package	$comp_1$	$comp_2$	$comp_3$	$comp_4$	$comp_5$	$comp_6$	$	α_i
S_1	0	0	1	0	0	0	12046.00	1.0
S_2	1	0	0	0	0	0	11690.35	1.0
S_3	0	1	0	1	0	0	27926.85	0.887
S_4	0	0	0	0	0	0	-	-
S_5	0	0	0	0	1	0	20447.00	1.0
S_6	0	0	0	0	0	1	49161.70	1.0

TABLE 4.3 – Optimized Maintenance Package Scenario

	Tasks Allocation						**Total Cost**	**Gain**
Package	$comp_1$	$comp_2$	$comp_3$	$comp_4$	$comp_5$	$comp_6$	$	α_i
S_1	0	0	1	0	0	0	12046.00	1.0
S_2	1	0	0	0	0	0	11690.40	1.0
S_3	0	1	0	1	0	0	27926.85	0.887
S_4	0	0	0	0	0	0	-	-
S_5	0	0	0	0	1	1	54296.20	0,780
S_6	0	0	0	0	0	0	-	-

Figure 4.1 shows the preventive maintenance accumulated cost of each package in the life-cycle. The tests included the six components in a horizon of 30.000 FH using the original task arrangement and the best optimization result.

The improved maintenance plan demonstrates a 2.25% improvement compared to the original task arrangements. The benefit is associated with the cost reductions achieved by combining the engine and hydraulic pump maintenance tasks, which include sharing specific common preparatory activities.

Both the original and optimized allocations did not consider including tasks in the package S_4. This is justified by the fact that the losses of flight hours of components, which have limitations beyond 3000 FH, do not result in significant gains in the corrective maintenance cost or in savings due to the packaging.

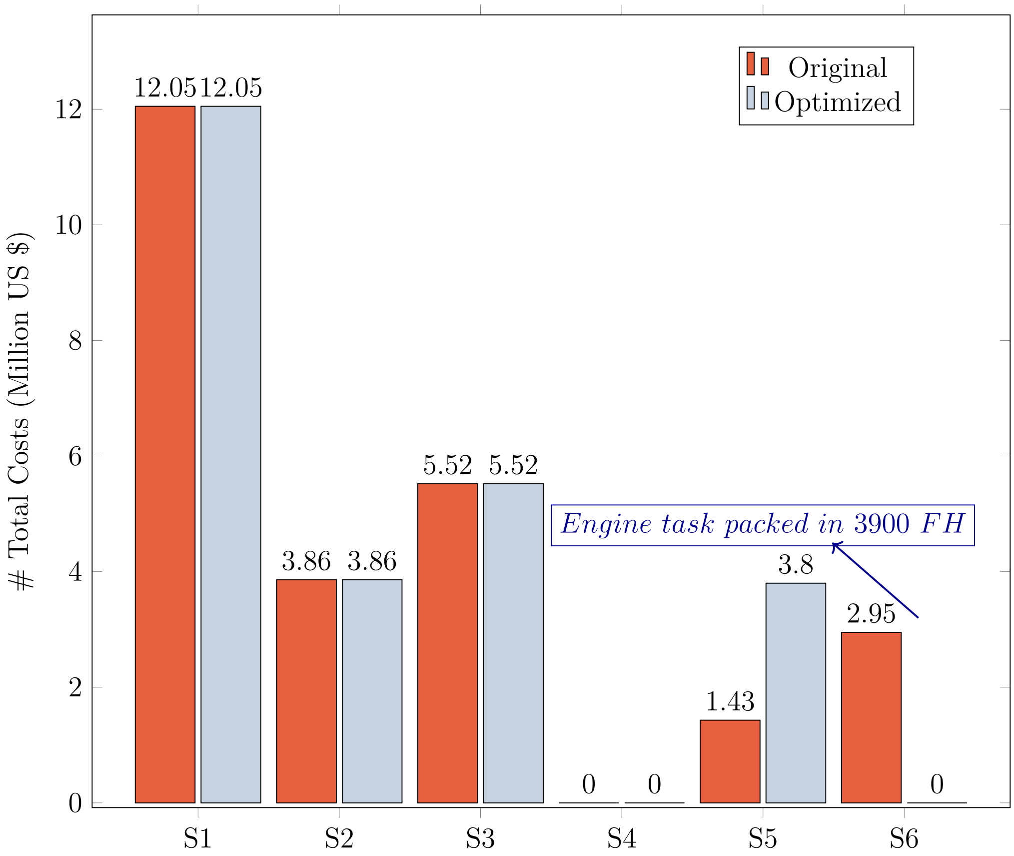

FIGURE 4.1 – Economy Validation - Cost of Packages in the Lifespan
The Packages are are in the horizontal axis

Table 4.4 shows the total accumulated preventive maintenance costs and the packaging economy resulting from the optimized solution.

TABLE 4.4 – Accumulated (**PM**) Total Cost and Packing Gain

Scenarios	**Cost** (M$)	**Economy** (M$)	**Gain** (%)
Original	$ 2.580.012,75	-	-
Optimized	$2.521.986,95	58.025,80	2,25%

The gain of 2.25% is notable due to its limited scope, since it only considers the influence of packaging on a small sample of 6 activities, which represents a small fraction of the entire maintenance plan.

The next paragraphs will show also the contribution of the corrective maintenance in the total costs. The tests in this phase considered several experiments, including 32 of then using the evolutionary algorithms provided by MicrosoftExcel$^{\circledR}$ in an attempt to solve the problem more successfully than the initial task distribution. The first eleven tests are shown in the Tables4.5 and 4.6. The remaining tests have similar results.

TABLE 4.5 – Experiments with: Evolutionary Algorithm (Allocations)

	$comp_1$	$comp_2$	$comp_3$	$comp_4$	$comp_5$	$comp_6$
Original	900	1500	300	1500	3900	4800
Test 1	900	900	300	900	3900	4800
Test 2	900	1500	300	900	3900	3900
Test 3	900	1500	300	1500	3900	3900
Test 4	900	1500	300	1500	3000	3000
Test 3	900	1500	300	1500	3900	3900
Test 6	300	1500	300	1500	1500	4800
Test 7	900	1500	300	1500	3900	3900
Test 8	900	900	300	1500	3900	3900
Test 9	900	1500	300	1500	3900	4800
Test 10	900	1500	300	900	3900	3900
Test 11	900	1500	300	1500	3000	3000

TABLE 4.6 – Experiments with: Evolutionary Algorithm (Costs)

	($ CM)	**($ PM)**	**($ Total)**	**Gain**
Original	811,530.50	2,587,012.75	3,398,543.25	–
Test 1	903,170.74	2,742,161.20	3,645,332.54	$-6,77\%$
Test 2	860,033.78	2.702.501,20	3.562.534,98	$-4,60\%$
Test 3	810,848.33	2,521,986.95	3,332,835.28	$+1,97\%$
Test 4	814,331.17	2,684,875.55	3,499,206.72	$-2,88\%$
Test 5	810,848.33	2,521,986.95	3,332,835.28	$+1,97\%$
Test 6	814,331.17	2,684,875.55	3,499,206.72	$-2,88\%$
Test 7	810,848.33	2,521,986.95	3,332,835.28	$+1,97\%$
Test 8	853,303.14	2.709.990.50	3.563.293.64	$-4,62\%$
Test 9	811,530.50	2,587,012.75	3,398,543.25	0.0%
Test 10	860,033.78	2,702,501.20	3,562,534.98	$-4,60\%$
Test 11	814,331.17	2,684,875.55	3,499,206.72	$-2,88\%$

PM Preventive Maintenance **CM** Corrective Maintenance

Even with a reduced solution space, the findings suggest that heuristic approaches could discover better solutions, whereas certain tests provide outcomes with costs that are the same or greater than the initial packing. The original task allocation is based on a real airplane maintenance plan information.

The Figure 4.2 shows a pictorial view of the same tests. It should be noted that the cost of corrective maintenance represents a small percentage of the total cost. This fact is expected due to the high reliability of the components used in the aeronautical industry.

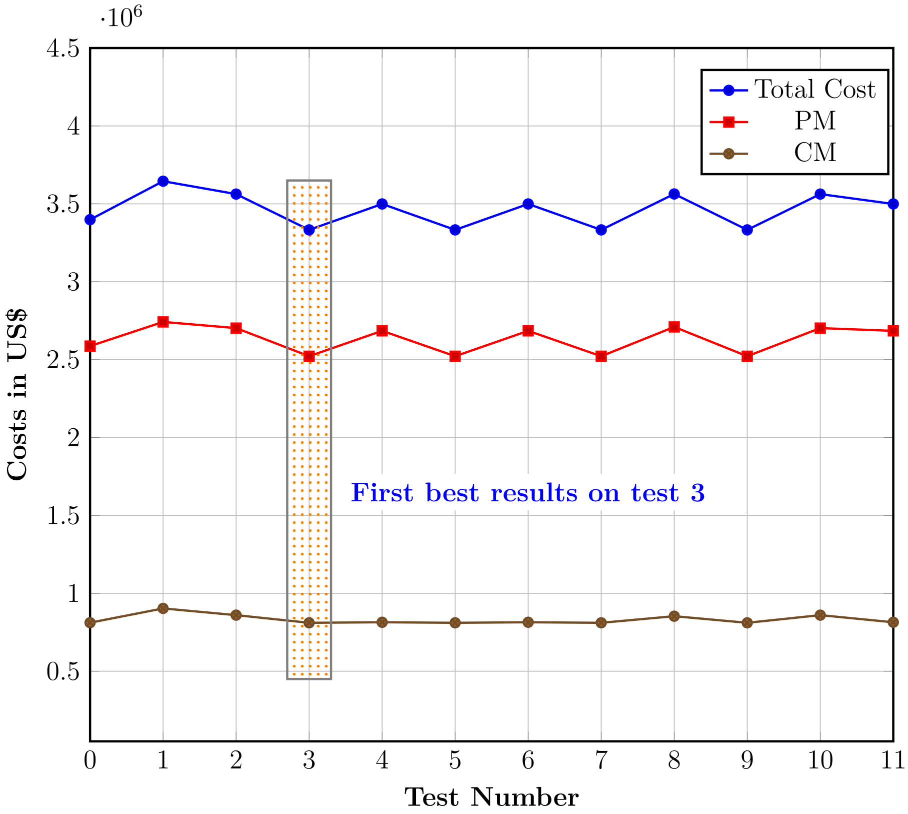

FIGURE 4.2 – Summary of Preliminary Tests

The Test identification is in the horizontal axis

PM Preventive Maintenance **CM** Corrective Maintenance

The picture also illustrates the model's reaction to variations in costs. An increase in preventative maintenance expenditures typically leads to a decrease in corrective costs. The least favorable outcome occurred in test 1, with both prices rising, while the most favorable result is seen in test 3, 5 and 7. Table 4.5 shows that the difference between the original and best solution is the allocation of the Engine maintenance task, component $comp_6$, together with the Hydraulic pump, component $comp_5$ at 3900 FH. This data demonstrates the positive economic impact of coordinating tasks that include shared preparatory activities.

A more complex scenario was developed after the first testing, incorporating a larger number of tasks and package alternatives. This scenario was designed to evaluate packages with different steps. The model was exported to the Python environment and improved to enhance flexibility and analysis.

It was used the *Branch-and-Cut* method to resolve several scenarios. It is a very effective solution for resolving a number of Integer Programming problems, and it can also ensure optimality (ALMGREN *et al.*, 2012).

The IP solver utilized is the CoIN-OR CBC, created by Forrest *et al.* (2020) and managed by a small team of volunteers affiliated with the non-profit COIN-OR Foundation. Thus, it was feasible to examine the expected achievements and assess the outcomes. The goals examined in this study are:

> H1: Achieving cost minimization due to task grouping around common resources or preparations, as well as task grouping around near maximum useful life, which was confirmed.
>
> H2: Obtaining gain in availability with organizing the task sequence in the same packing, which was confirmed.
>
> H3: The system would be able to improve cost minimization by exploring historical data, which was partially verified to be possible after four or five maintenance cycles simulations. Nevertheless it is necessary to proceed with a more detailed studies in the future works.

Many tests were conducted using diverse subsets of tasks generated from a list of 85 aircraft components to verify the model adherence to the three hypothesis. A flight horizon of 5000 hours was considered in the experiments of 20 FH, 50 FH , 100 FH, 150 FH and 200 FH. The Figure 4.3 depicts the difference in preparation cost for each step.

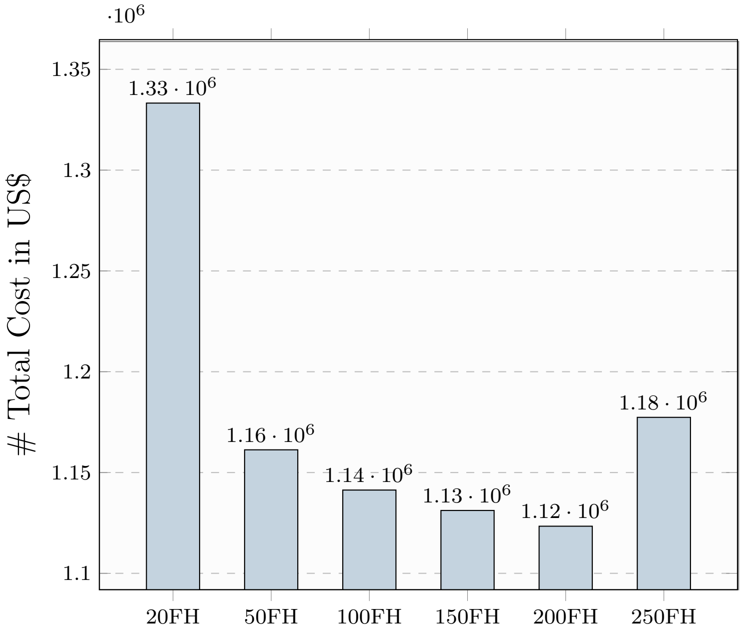

FIGURE 4.3 – Preparation costs for different steps

The results indicate that up to 200FH, the greater the step interval, the greater is the economy with preparation activities which in turn should contributes to optimize the total maintenance costs. It should be noted that 200FH is the lowest maintenance limit in this component sample being tested. A better gain in the task allocation when using the 200 hours-step is explained by the fact that in this sample, more tasks is considered for inclusion in a same package and thus having less out-of-phase activities.

The Figures 4.4 and 4.5 show a pictorial view of the distribution of tasks along the 5000 FH horizon for the 25-hours and 150-hours steps, respectively. It confirms a better packaging effect for 150-hour steps in comparison with 25-hours step.

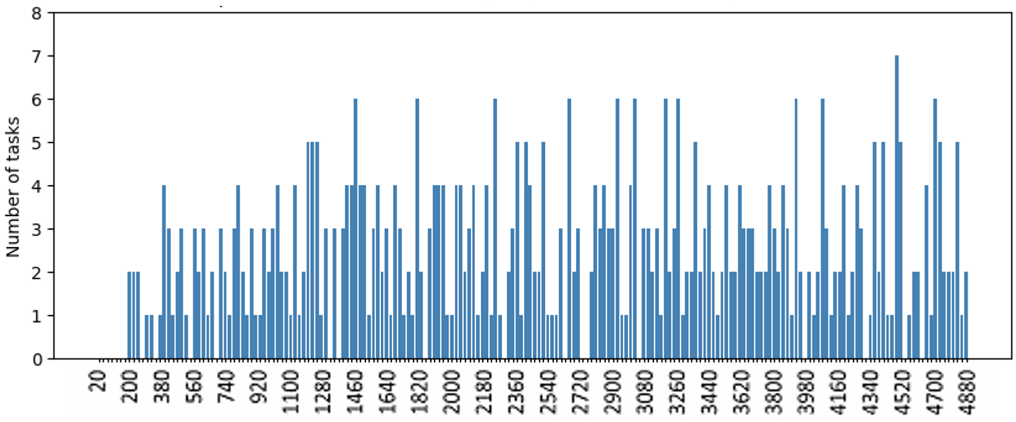

FIGURE 4.4 – 25-hour Steps Tasks Distribution

The efficiency of packaging in the economy can be observed in Figure 4.6, which display the results before considering the impact of packaging, and Figure 4.7, which

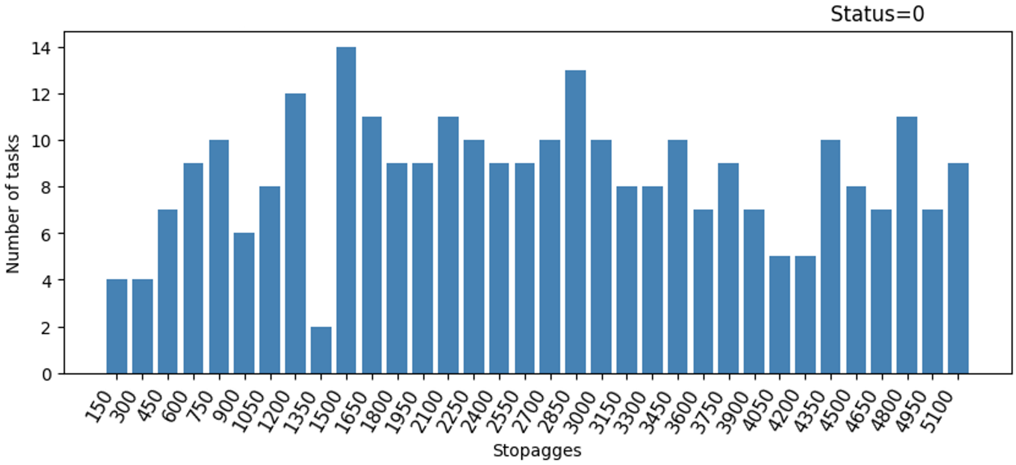

FIGURE 4.5 – 150-hour Steps Tasks Distribution

show the results after optimizing packaging. The results are obtained from experiments that analyze 85 components over a time span of 5000 flight hours, with a step interval of 150 flight hours after a total of 20 iterations.

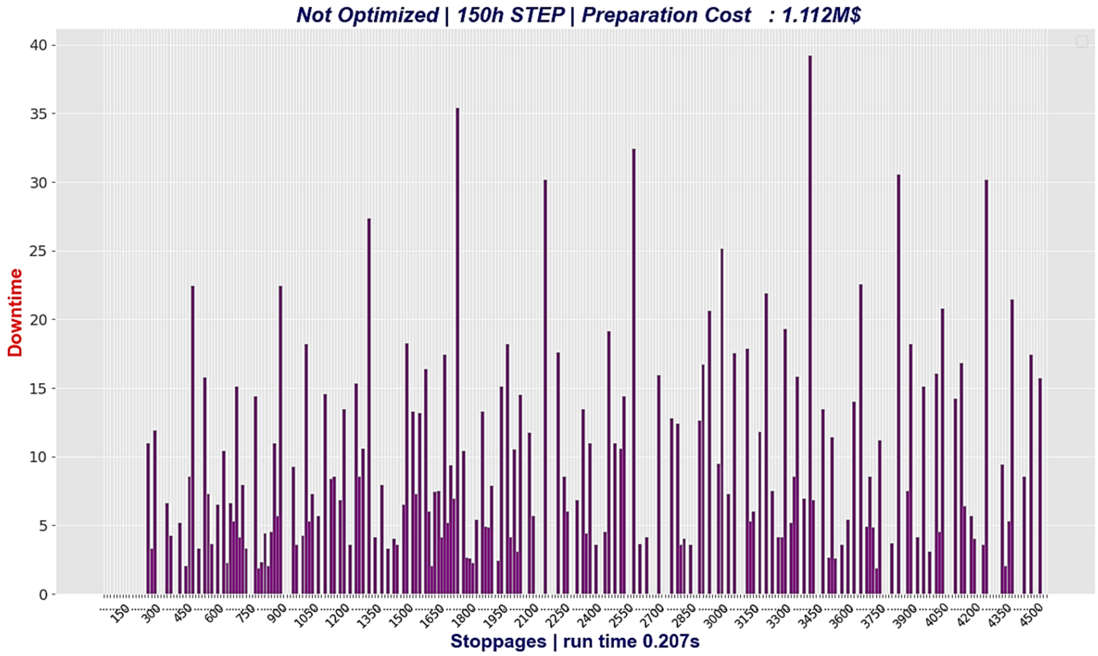

FIGURE 4.6 – Not Optimized Preparation Costs

Table 4.7 shows the values of costs and gain in the preparation costs after optimization that includes the concept of savings of sharing preparatory tasks in the maintenance plan definition.

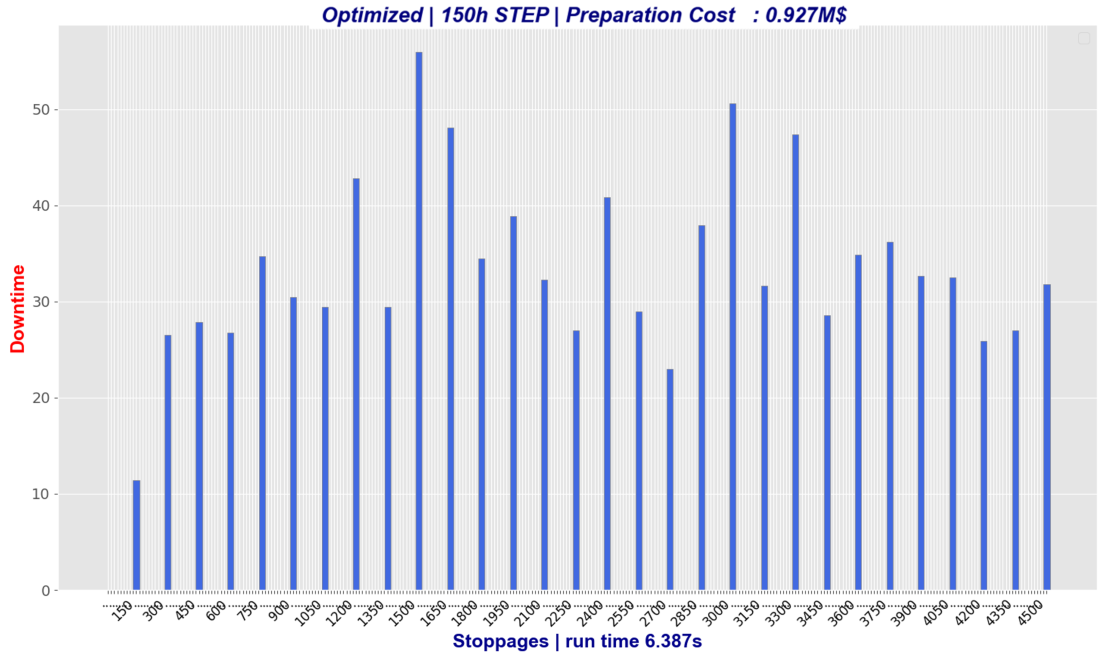

FIGURE 4.7 – Optimized Preparation Costs

TABLE 4.7 – Influence of Packaging Optimization - 150h steps - 5000h

Optimization	**Total cost ($)**	**Reduction ($)**	**Gain**
NO	1,111,566.15	-	-
YES	926,539.56	- 185,026,59	16,65%

As seen, there is a notable decreasing of 16,65% in the costs related to the preparation activities after the use of the optimization model. This gain is related only to the savings obtained by sharing the preparatory tasks. The influence of the item probability of failure and respective corrective maintenance cost is tested in the next experiments.

To validate the impact of corrective maintenance, optimization tests with four alternatives as depicted in Table 4.8 were performed.

TABLE 4.8 – Configuration of test samples

	Test Configuration	
Test Label	**Sample characteristic**	**Failure Probability**
[**OptRep+38%**]	38% have age-related degradation	Considered
[**NotOptRep+38%**]	38% have age-related degradation	Not Considered
[**OptRep+100%**]	100% have age-related degradation	Considered
[**NotOptRep+38%**]	100% have age-related degradation	Not Considered

The evaluation of each test option considered 85 tasks, 200-hours steps. The evaluation was conducted over a period of 10000 flight hours, with a standard annual flying time of 1500 hours. Table 4.9 illustrates the overall expenses when the inclusion of failure probabilities is taken into account in the model, as well as when it is not. The percentages of gains is given by comparing the results for the sample having the same characteristics.

TABLE 4.9 – Influence of Corrective Cost - 200h steps - 10000h

Scenario	**Total cost**	**Cost reduction ($)**	**Gain (%)**
NotOptRep+38%	5,418,980.05	-	-
OptRep+38%	5,297,470.48	- 121.509.57	2.3
NotOptRep+100%	6,796,461.43	-	-
OptRep+100%	5,339,925.64	- 1,456,535.79	27

Table 4.9, shows that the consideration of likelihood of handling corrective maintenance in the optimization implied in a significant difference in the total costs in tests with 38% and 100% of repairable items. Tests conducted on a sample with 38% of items experiencing aging-related deterioration revealed a cost reduction impact of 2.29% (equivalent to about US$121,509.57) in the optimization process.

Furthermore, it should be emphasized that apart from the financial expenses, an unforeseen malfunction might lead to unforeseen consequences, such as passenger discontent and disruptions to the aircraft's flight schedule, depending on the specific failure situation. Additionally, it is worth mentioning that this impact becomes more pronounced when additional components with degrading characteristics are included in the test.

The maintenance cost reduction with optimization, in comparison with an allocation based only in the maximum intervals, is composed of a economy regarding the consideration of failure probability plus the preparation cost economy.

Tests regarding the task grouping around common resources, indicates a reduction in preparation costs (around US$185,026.59 or 16.65%), guaranteeing resources or preparation costs were accounted for just once per package. Tests considering the probability of failures in the optimizations shows also a reduction in the corrective maintenance costs (around US$121,509.57 or 2.29%). Thus, demonstrating a significant improvement in a total cost reduction and confirming the achievement of [H1] goal.

Additional tests with 85 tasks considering a standard operational profile (1500 flight hours per year) and 5000-hours horizon, were conducted to confirm the objective [H1]. The Figure 4.8 shows the task allocation based only in their interval limits and Figure 4.9, shows the results and gains after optimization considering the savings in the preparatory activities and probability of corrective maintenance .

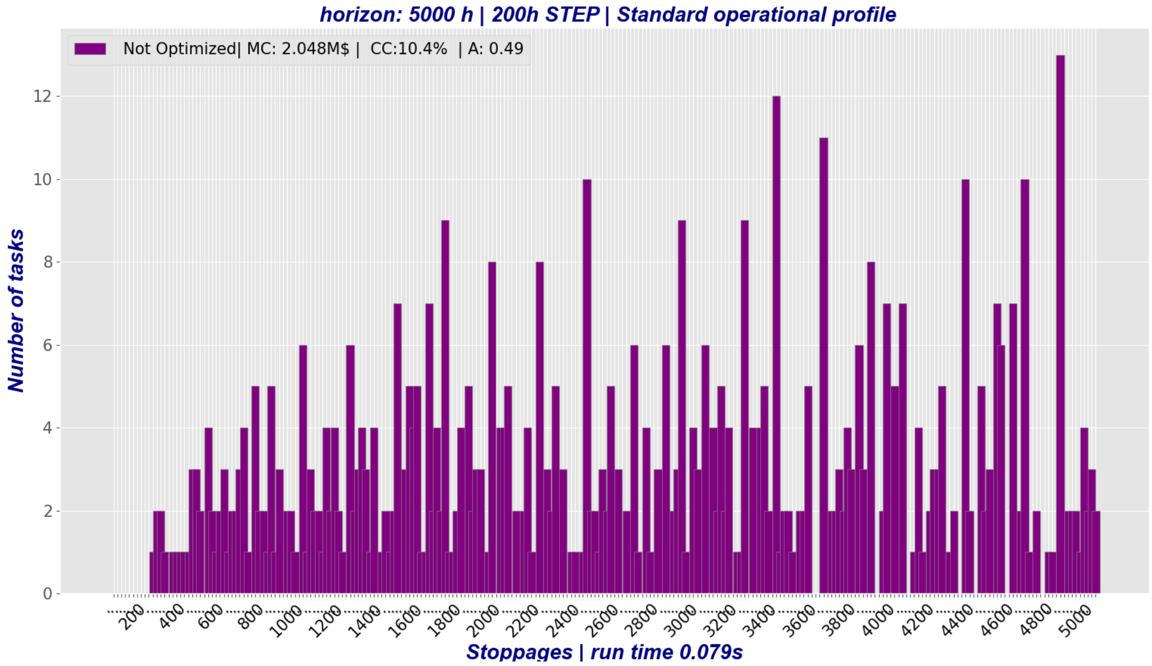

FIGURE 4.8 – 200-hour Steps Tasks Distribution Without Optimization

PMC Preventive Maintenance Cost **CMC** Corrective Maintenance Cost

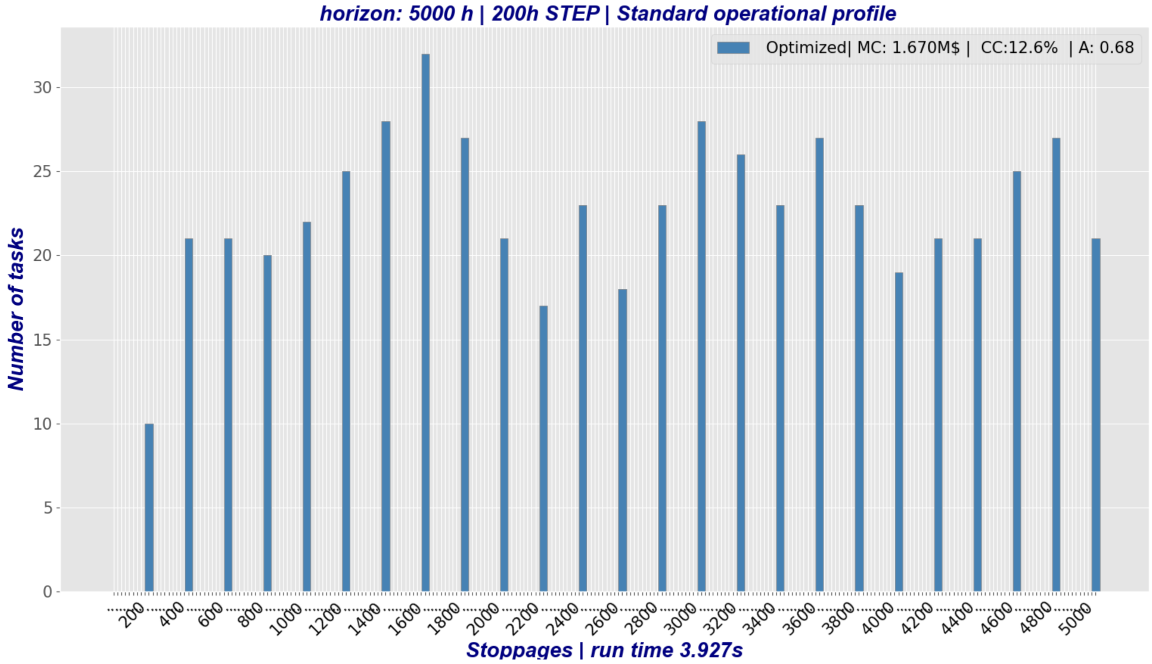

FIGURE 4.9 – 200-hour Steps Tasks Distribution With Optimization

PMC Preventive Maintenance Cost **CMC** Corrective Maintenance Cost

The model's efficiency may be emphasized through its optimization in terms of costs and availability.

After optimization, the overall costs were reduced by about US$377,639.13, which represents a decrease of 18.44%. This reduction was achieved by considering the economy on corrective maintenance, and ensuring that preparatory costs were only accounted for once per package, while also allocating tasks to packages in the most efficient way possible. This validate the objective [H1] of obtaining gains in maintenance costs since the beginning of operation.

It is noticed also a significant gain of 19% in the availability, thus confirming the objective [H2] regarding obtaining improvement in the aircraft availability and, a decreasing in the costs related to the corrective maintenance of US$3,359.41 representing a reduction of 1.57%, that should imply in a better reliability performance of aircraft.

4.1.1.2 Initial Learning Capability Test

During this preliminary phase, more tests were done to see if the hypothesis (H3) was true.

Prior to the learning process, an analysis for feature selection was conducted to choose the most relevant characteristics from the simulated historical records to be utilized in the ML prediction model. The learning process for the cost and availability mapping functions takes into account the maintenance date, man-hours spent, material consumption prices, and operational hours as independent input variables.

The simulated maintenance records are generated during each execution of the model and then registered in a file. The learning module reads the data, and the supervised learning module determines the mapping function, a ML prediction model, for each component. This process is used to obtain the parameters for the solver.

The solver receives as input the result of the prediction model and solve the problem with the new parameters.

Figure 4.10 shows the outcomes of using the learning capacity after four cycles of maintenance.

The test indicates that planner gained knowledge by evaluating past data generated by the optimizer throughout each maintenance cycle. This suggests that H3 confirmation is a possibility. By adding machine learning features to the proposed optimization framework, the system would improve the maintenance plan by using data from the simulated operation and maintenance. Nonetheless, more testing and investigation are required. It is expected that the rising number of maintenance records created in future studies using field records will provide an acceptable level of confidence in this method.

In summary, the supervised learning can be used to determine the mapping function, which involves transforming new input data (maintenance records and events) to produce new output values and adjustment in the maintenance plan. However, further studies and

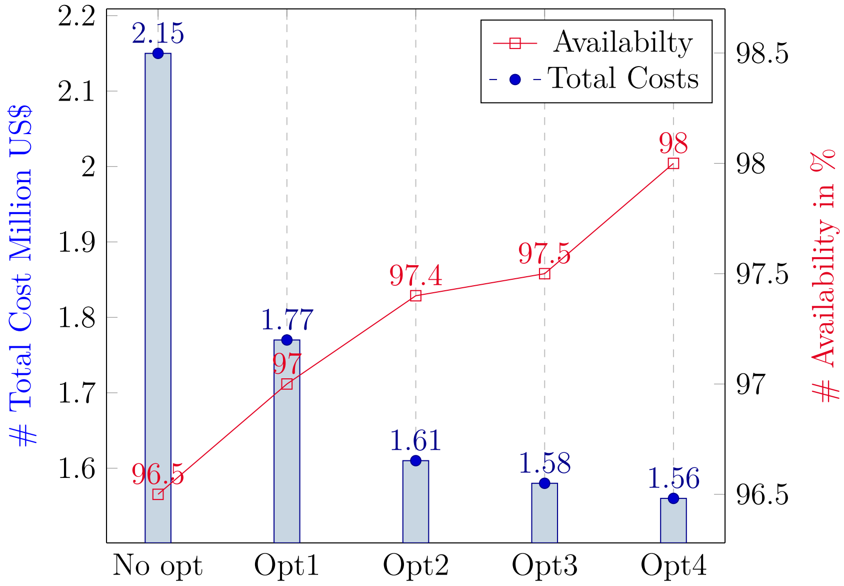

FIGURE 4.10 – Results of ML Prediction
The optimization cycle are in the horizontal axis

testing are required to validate the evidence of [H3].

4.1.2 Final Tests

In order to enhance the model, a module to sequence the tasks in each maintenance package was included. Sequencing is used by the maintenance planning sector to determine the order of execution for each activity during the maintenance stoppage. The model employs resource availability, according to the mechanic skill, tasks relationship and zone limits criteria. Several experiments were performed to finally confirms the achievement of research objectives.

4.1.2.1 Influence of interval steps

A set of tests were conducted using diverse subsets of components and steps of 20h, 50h, 100h, 150h and 200h steps.

The Figure 4.11 depicts the results of the experiments with 85 components with different maintainability and failure rate parameters, and intervals ranging from 200 FH to 1870 FH. The tests consider a 4500 FH horizon and a standard operational profile (1500 flight hours per year).

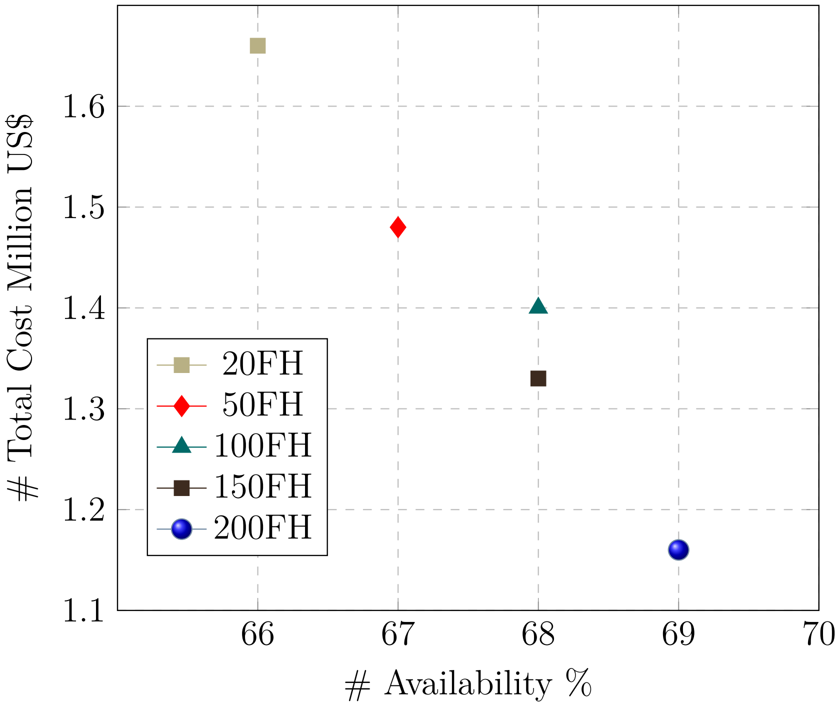

FIGURE 4.11 – Influence of Step interval

The findings suggest that, within the tested sample, there is a positive correlation between the step interval and both the economy and availability, up to the minimal task interval.

4.1.2.2 Test of *ETAPPS + FFD* method efficiency

The Tables 4.10 to 4.13 shows the results of the final tests performed to assure the confirmation of H1 and H2. For each case, four conditions were created based on the methods used on the experiments as defined below:

1. Simple: Simulation of task allocation without optimization considering only the good engineering decision based on the maximum interval limits
2. Simple + FFD: Simulation of task allocation followed by a minimization of downtime with Fist-Fit Decreasing *FFD* algorithm.
3. ETTAPS : Optimization of task allocation using the Efficient Task Allocation and Packing Problem Solver *ETTAPS* Solver.
4. ETTAPS + FFD : Combination of optimization by ETTAPS and minimization of downtime by FFD for downtime optimization.

To generate Tables 4.10 to 4.13 , it was ran 20 instances with 85, 170, 255 and 340 tasks each (one task per component), with a 200h step, by using the *Simple* method, as well as *ETAPPS* with and without *FFD*. The values are the averages of these 20 instances run.

Table **??** displays the outcomes of 20 run with 85 task and a 200h step.

TABLE 4.10 – Experiments results: 85 tasks

Method	**FFD**	**Availability**	**Maintenance cost ($)**	**Corrective cost ($)**	**Runtime (ms)**
Simple	no	0.54	1,650,224.73	184,663.80	33
	yes	0.59	1,661,193.22	181,419.00	144
ETAPPS	no	0.70	1,458,388.19	173,306.93	3803
	yes	0.79	1,448,379.20	173,755.21	3421

Table 4.11 displays the outcomes of 20 run with 170 task and a 200h step.

TABLE 4.11 – Experiments results: 170 tasks

Method	**FFD**	**Availability**	**Maintenance cost ($)**	**Corrective cost ($)**	**Runtime (ms)**
Simple	no	0.51	2,438,328.10	220,897.97	53
	yes	0.55	2,458,025.91	219,872.59	217
ETAPPS	no	0.68	1,891,234.98	209,519.68	546
	yes	0.76	1,904,401.21	214,702.81	680,7

Table 4.12 displays the outcomes of 20 run with 255 task and a 200h step.

TABLE 4.12 – Experiments results: 255 tasks

Method	**FFD**	**Availability**	**Maintenance cost ($)**	**Corrective cost ($)**	**Runtime (ms)**
Simple	no	0.49	2,575,235.09	230,650.08	85
	yes	0.54	2,527,619.58	235,783.80	335
ETAPPS	no	0.66	2,170,745.99	227,630.87	6986
	yes	0.73	2,169,053.57	223,530.32	8102

Table 4.13 displays the outcomes of 20 run with 255 task and a 200h step.

TABLE 4.13 – Experiments results: 340 tasks

Method	FFD	Availability	Maintenance cost ($)	Corrective cost ($)	Runtime (ms)
Simple	no	0.48	2,881,688.26	245,706.75	55
	yes	0.53	2,895,412.32	249,707.66	999
ETAPPS	no	0.65	2,391,469.34	239,126.70	8187
	yes	0.75	2,385,380.67	236,433.82	8187

As expected while the number of tasks increase the availability decreases and the total cost increases, since more tasks are included in each stoppage. Nevertheless, the *ETAPPS + FFD* method shows a better performance than the Simple method, that simulate a allocation of tasks only considering its maximum interval. *FFD* algorithm keeps its efficiency in the improvement of the availability. The *ETAPPS* method also confirms its efficiency presenting better results in terms of availability increase and cost reduction when compared with Simple method. The costs in the tests using *FFD* have increased slightly, which can be explained by changes in task settings from one configuration to another.

It also confirms that with *FFD* method the tasks are better packed leading to an increase on the aircraft availability. Figures 4.12 and 4.13 presents a pictorial view of the results regarding respectively to the total costs and to the inherent availability based on the number of tasks and the four distinct methods.

It is notable that for any numbers of tasks the method ETTAPS achieved better results than the Simple method. Also, the use of task sequencing using the FFD algorithm taking in account the relationship of tasks, zone limits and mechanic resource available, improve the aircraft availability in all scenarios.

Figure 4.14 presents a summary of the improvements achieved in the tests mentioned above. The gains are calculated by comparing the results obtained with the utilization of the *ETTAP+FFD* optimization method and results from the non-optimized *Simple+FFD* approach.

The results indicate an average increase of 16.8% in overall expenses and 20.5% in availability. These notable accomplishments validate the efficacy of the model, hence verifying the achievements of the research project objectives.

Table 4.14 demonstrates the effect of the *OP* factor on the number of *Out of Phase* assignments. This factor should be defined based on the operator's options to offer them the desired operational and maintenance flexibility.

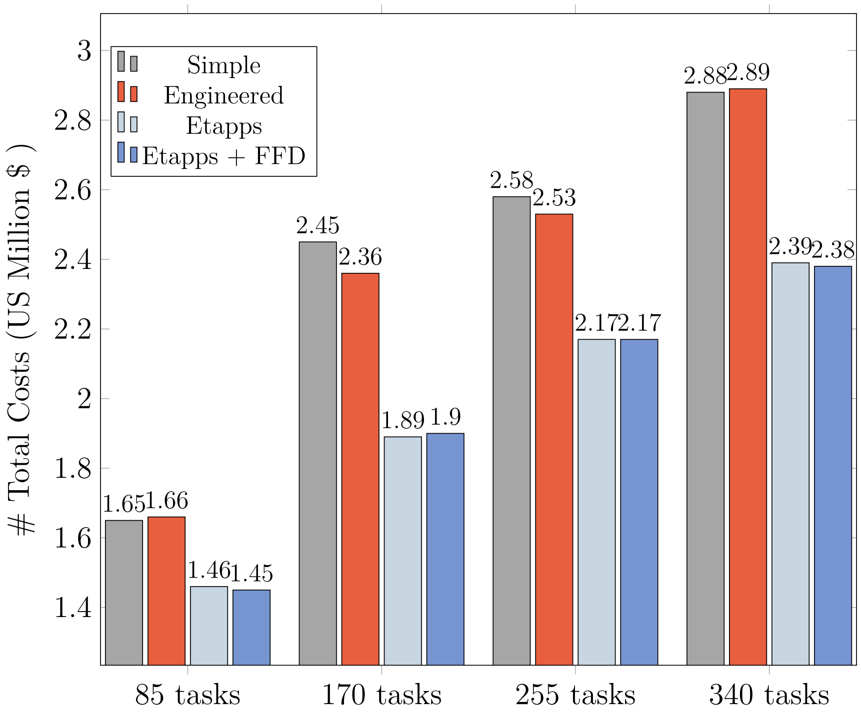

FIGURE 4.12 – Result Plot - Total costs

The numbers of components are in the horizontal axis

The Total Costs (US $) is in the vertical axis

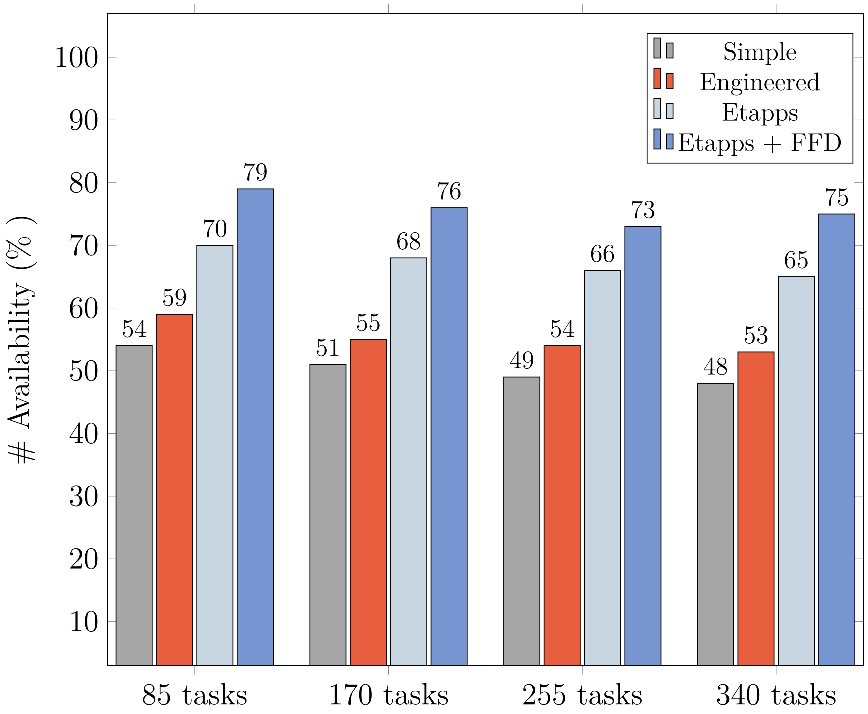

FIGURE 4.13 – Results Plot - Availability

The numbers of components are in the horizontal axis

The availability (%) is in the vertical axis

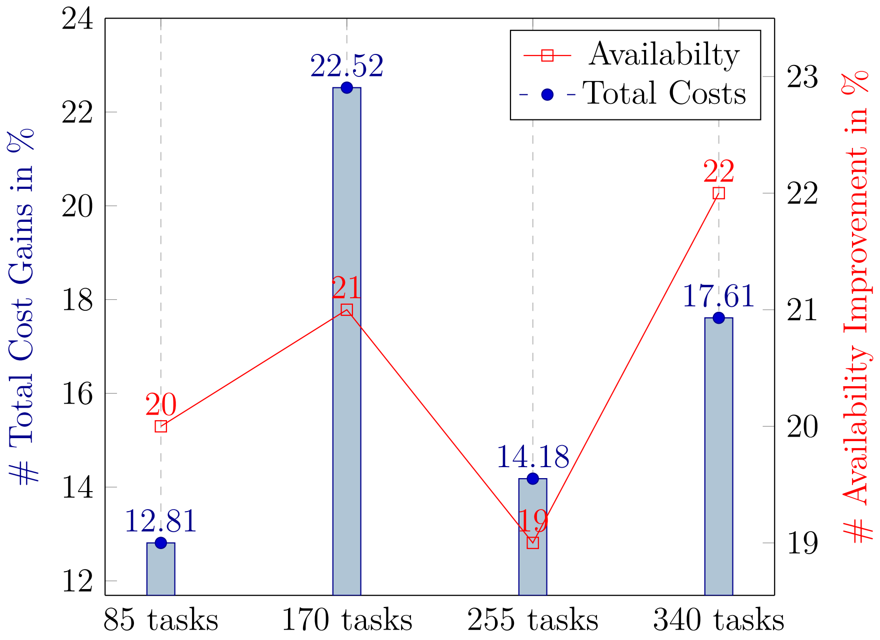

FIGURE 4.14 – Summary of gains in costs and availability
The numbers of tasks are in the horizontal axis

TABLE 4.14 – Experiments results: 340 tasks with out-of-phase

Method	FFD	A	Tot. cost ($)	Corr. cost ($)	Runtime (ms)	factor	Packed	OP
ETAPPS	yes	0.96	2,092,654.92	53,302.18	23,639	5	234	40
	yes	0.95	2,079,136.68	76,652.97	23,390	7	279	0

Tests using additional set of tasks were run to confirm and validate the hypotheses of gains in terms of costs and availability and the efficiency of the solver. The Figure 4.15 summarizes the results of 20 experiments considering a 200 FH step interval, standard operational profile (1500 flight hours per year) in a 4500 flying hours horizon, using the Simple and the ETTAPS methods.

A decrease in overall expenses amounting to approximately US$100,000.00, or 7.92% over a period of 4500 flight hours, was observed when comparing the outcomes achieved through the utilization of the ETTAPS optimization approach (shown by light-blue bars) with those acquired through the non-optimized SIMPLE method (represented by purple bars). This means that the ETTAPS assure the best possible allocation of tasks to packages, guaranteeing resources or preparation costs were accounted for just once per package. There has been a reduction in the expenses associated with corrective maintenance, amounting to US$6,150.00, indicating an improvement in the overall reliability of the aircraft.

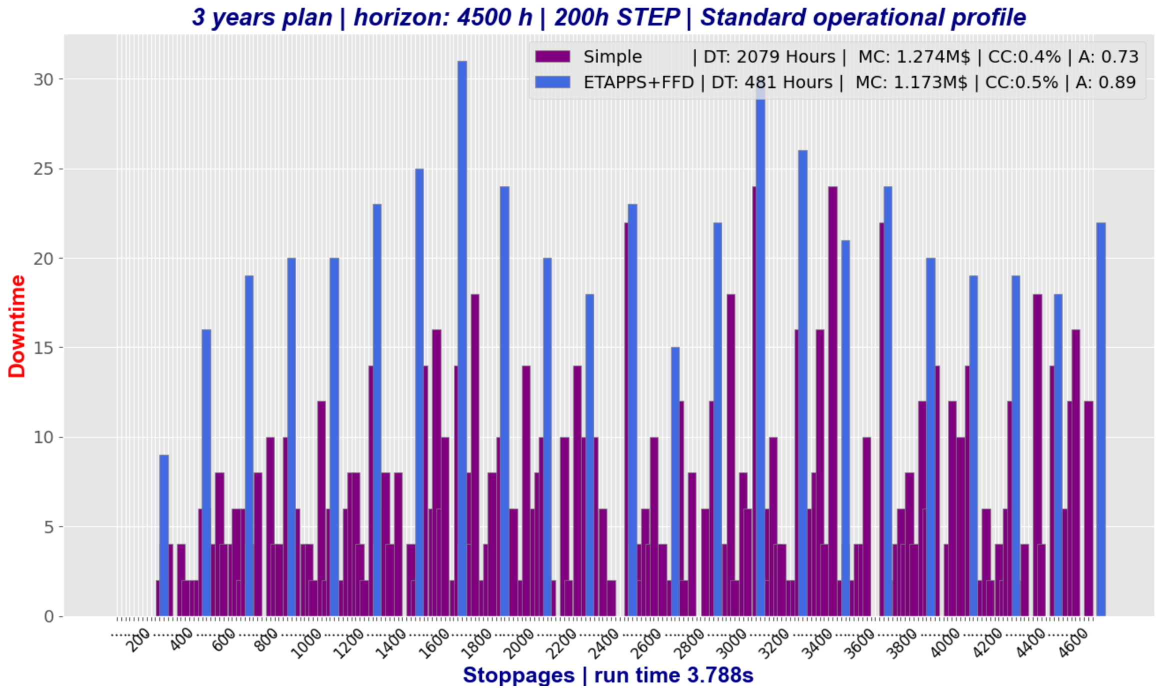

FIGURE 4.15 – Comparison of methods with 200-h steps

A noteworthy increase of 16% in the total availability is observed when employing the ETTAPS+FFD method, as indicated by the blue bars. The utilization of the FFD algorithm after the first optimization with ETTAPS serves to reduce the downtime, by effectively arranging the execution of tasks inside each work package.

4.1.2.3 Final ETAPPS method tests

Finally, a set of 700 maintenance and 665 preparation tasks, synthetically generated based on data of typical commercial aircraft were used to test the robustness of model and solution method as concerning the number of tasks. It includes tasks from system, structural and Zonal programs, with different usage parameters, flight hours (FH), flight cycles (FC) and months (MO).

The Figure 4.16 shows a general view of the task distribution for a period of 10 year equivalent to 25000 hours, taking into account a standard operational profile (2500 FH/Year and 1.33 FH/FC).

Despite the inclusion of an anticipated pre-packaging consideration in this test sample, the ETTAPS+FFD method presents a better allocation of tasks, as shown in the Detail 1 of the Figure 4.16. Although the simple method exhibits a lower downtime value at each maintenance stoppage, it results in a significantly higher number of stops, hence leading to an increase in total unavailability.

Tables 4.15 to 4.15 summarize the average results of 20 experiments considering a 400

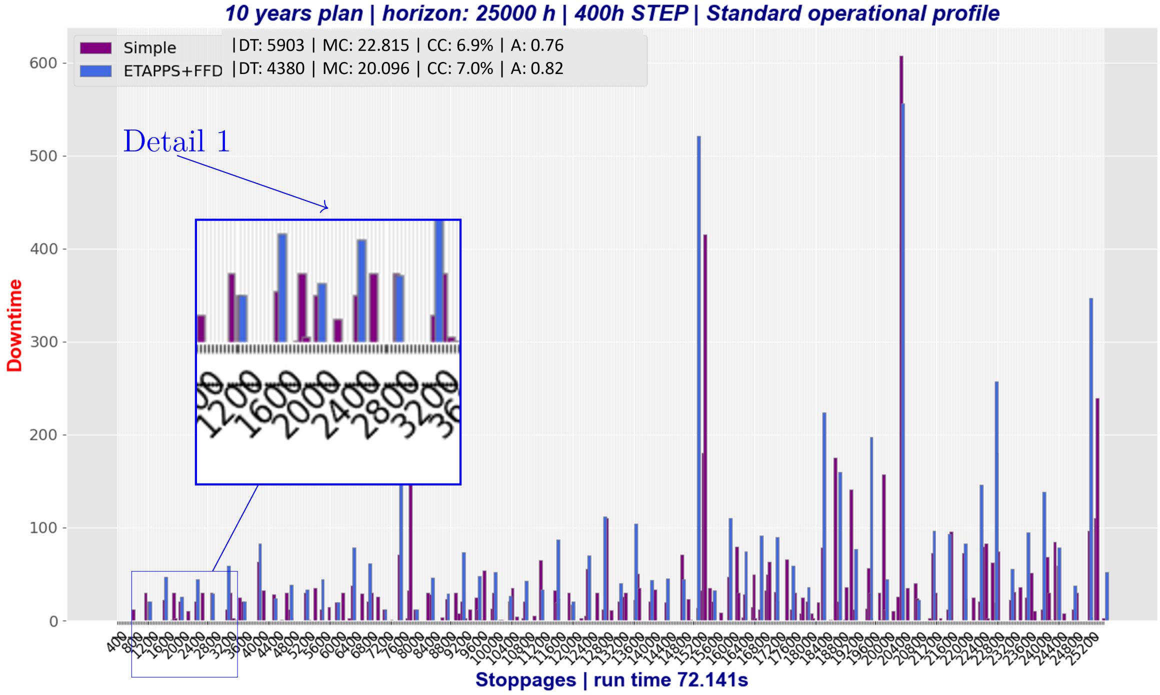

FIGURE 4.16 – Comparison of methods with 400-h steps and 700 tasks

FH step interval, and three different operational profiles in a horizon of 10 years, using the Simple, ETTAPS and ETTAPS+FFD methods.

TABLE 4.15 – Experiments results: 700 tasks and Low profile

Method	FFD	Availability	Total cost ($)	CM cost ($)	FH cost ($/FH)	Runtime (ms)
Simple	no	0.4577	16,237,702.64	977,344.60	2,165.03	0.214
ETAPPS	yes	0.6079	14,106,573.70	836,778.20	1,880.88	100.010

TABLE 4.16 – Experiments results: 700 tasks and standard profile

Method	FFD	Availability	Total cost ($)	CM cost ($)	FH cost ($/FH)	Runtime (ms)
Simple	no	0.7639	22,815,444.79	1,576,749.96	912.62	7.71
ETAPPS	yes	0.8248	20,096,094.56	1,418,235.53	803.84	80.726

TABLE 4.17 – Experiments results: 700 tasks and High profile

Method	**FFD**	**Availability**	**Total cost ($)**	**CM cost ($)**	**FH cost ($/FH)**	**Runtime (ms)**
Simple	no	0.8155	34,084,063.32	2,560,658.78	757.42	1.670
ETAPPS	yes	0.8690	29,641,446.46	2,319,645.48	658.70	153.476

The gains in both total cost and availability validate the effectiveness of utilizing the *ETAPPS + FFD* optimization model, even when dealing with this sample that includes several tasks with similar interval as it was pre-packaged. While not endorsed by the MSG-3 methodology, the pre-packaging concept can be observed in early MSG-3 analyses. It consider a definition of baseline intervals for A and C checks and then, the tasks, as are being created, are included in one of these checks and multiples.

The results also demonstrate a positive correlation between the aircraft's yearly usage and availability, indicating that as the utilization grows, the availability improves. This may be attributed to the fact that in this particular sample, over 50% of jobs come from the Structural and Zonal program, which are planned using time intervals measured in months (24, 48, 72, and 96 months).

These tasks will be incorporated into the scheduled stoppages regardless of aircraft use. The relationship between aircraft uptime and the length of time it operates within a certain time frame, as well as the relationship between aircraft downtime and the number of planned tasks, indicates that the aircraft's availability will grow as it is employed more frequently throughout the years.

4.2 Conclusion

This Chapter provided a comprehensive overview of the tests conducted to validate the effectiveness of the suggested model. The tests have different sizes, with the smallest being a sample of only six tasks. This sample was used for the initial test to evaluate the model's behavior.The most extensive test comprises 700 tasks, which represent nearly half of the maintenance plan devised for a regional aircraft. This sample includes system, structural, and zonal requirements. The data consistently demonstrated that the utilization of the *ETAPPS + FFD* model, developed in this study, results in an optimal distribution of tasks. This allocation leads to improved cost performance and availability compared to the conventional method, which only takes into account the limits of task intervals.

It is important to mention that the model can perform effectively and with less computing resources, even in complex scenarios with different utilization profile and a large number of tasks. This suggests that the model is capable of meeting the needs for creating a comprehensive maintenance plan for any sector within the aviation industry.

This validates the successful accomplishment of the goals of this thesis, which are to establish a scientific framework for enhancing both cost efficiency [H1] and availability [H2] in the development of the maintenance plan. In addition, the framework incorporates a task packing method using the *FFD* algorithm, providing an additional gain in terms of the aircraft availability.

The goal of providing a resilient maintenance plan [H3] was partially confirmed in the test performed to verify the model learning capability. It is proposed that this feature should be investigated by future works.

The Chapter 5 contains the conclusion of this study and the description of the contributions and proposal for the next studies.

5 Conclusion

5.1 General Achievement

This study developed and tested an innovative model to efficiently solve the Task Allocation and Packing (*TAPP)*) problem, in the context of developing an initial maintenance plan, attending the primary objective of this study. The goal of a *TAPP* is to identify the optimal package for assigning maintenance tasks resulting from the aircraft MSG-3 and certification analysis and then ordering the execution of tasks included in the packages.

The study first focused on identifying possible areas for improvement in the creation of maintenance plan, being identified several points ranging from improvements in the MSG-3 analysis up to aircraft maintenance planning process. The study highlighted the *TAPP* as a significant issue that impacts both airlines and manufacturers. Then the research proposal was selected in order to optimize the consolidation of requirements from certification and MRB/MTB processes into packages with the goal of creating a maintenance plan that would enable the operator to efficiently manage its aircraft fleet.

Supportability engineers have the challenge of developing an effective maintenance plan that takes considers all crucial technical elements and operational scenarios, without relying on a scientific instrument to support this activity. The proposed model efficiently allocates tasks to maintenance stoppages and further organizes the execution of activities assigned in each package. The model partially addresses the deficiencies identified in the course of developing the maintenance plan. It fulfills an industry need by providing a method to efficiently support the creation of the operator maintenance plan.

The development of the proposed model has required the identification of the critical parameters which influence the maintenance cost and availability, and the exploration of optimization techniques that would be employed to solve the problem.

The problem is addressed in two stages: initially, the model efficiently assigns tasks to packages, ensuring that the component remains within its safe flight hour range and minimizing overall costs. Subsequently, for each work package, tasks are grouped using a "Bin Packing Problem" approach, where multidimensional tasks are organized into multidimensional bins in an effort to minimize downtime.

In addition, the study involves examining prior studies in this field to determine the key factors and approaches employed in the optimization process. This established a foundation for defining the model and technique of resolution to be utilized. The test findings indicate that the model possesses the ability to provide efficient solutions based in scientific methodologies and pertinent technical parameters.

For supportability engineers in the OEM, this framework helps them effectively allocate tasks for maintenance checks, considering the costs associated with preventive and corrective maintenance, the potential financial losses due to aircraft downtime, and the economic benefits of bundling tasks that need similar preparations. In addition, it can suggest an efficient order for completing tasks assigned to a package, leading to significant enhancements in aircraft availability. In addition, It is beneficial to highlight the significance of involving supportability engineers from the first phases of development to assess and assist in decisions that impact reliability and maintainability elements, and subsequently, the resulting maintenance plan.

At the operator side, the framework can assist in the creation of an Operator Approved Maintenance Plan (OAMP) that is a significant concern for the Production Planning and Control, Maintenance and Engineering, and Operations departments of an airline. Effective management of preventive maintenance necessitates evaluation of multiple factors and careful selection of the optimal strategy.

Individual requirements can be managed using a single task method or by grouping them into distinct packages (and eventually out-of-phase tasks). These decisions have a substantial effect on the efficacy of product supportability, especially at the tactical level for planning activities. In this regard, the model can support operators' engineering to evaluate each option and choose the best strategy to accommodate the diverse scenarios and objectives. Additionally, it can serve as a supplementary tool throughout the assessment process in collaboration with the manufacturer to develop a customized maintenance plan.

This study proved that grouping activities using the proposed optimization framework saves total maintenance expenses. Furthermore, the findings indicated that even when using aeronautical components with a low rate of failure, the likelihood of needing repairs, which was not taken into account by several authors and had a minimal effect on the optimization model decision, is an important factor to consider. This is because repairs incur indirect costs of failure and can impact the availability of the fleet.

The method provided extended the current maintenance planning studies by investigating how the sequence to perform each task within a package can influence the aircraft downtime using the FFD algorithm. For this, the optimization model took into account the available resources in each mechanic skill as well as the physical capacity of the zones, and the relationship between tasks.

The resolution strategy used the Branch and Cut algorithm, which is an exact solution approach capable of providing the optimal response to the problem and so assigning the tasks in the best package according to the solution space. The concept of bins and the First-Fit Decreasing (FFD) algorithm were used for the sequencing of the execution of the tasks within the package in order to improve availability.

The FFD algorithm first orders the items from the largest to the smallest and distributes them in each available space of each compartment. In the instance of the thesis, it reduces the number of task compartments while also reducing work package time and enhancing availability.

The optimized initial maintenance plan must be constantly updated in response to the evolution of reliability and maintainability data during the development phase, or with data from task execution and operational performance during the operation and services phase. This allows the maintenance plan to be resilient to changing scenarios and parameters.

In this regard, The study also investigated the potential of employing a learning mechanism to facilitate proactive data analysis, which might contribute to the development of resilient maintenance planning. Supervised learning was employed to conduct tests aimed at evaluating simulated maintenance execution data, specifically in terms of man-hours, downtime, and material. The purpose of these tests was to provide the necessary parameters as inputs for the optimization solver. The deep evaluation of machine learning (ML) tools and its use in a real-world context was not feasible due to the time constraints. However, the utilization of ML can contribute to the analysis of maintenance plan changes by facilitating the update process outlined in the Federal Aviation Administration (FAA) advisory circular 121-22 (C).

The test results have shown that the proposed model prevails over other conventional maintenance planner methods in terms of costs and availability. Therefore, it successfully achieves the objectives of the research proposal by providing a scientific tool to assist in the development of a maintenance plan that can enhance performance in terms of costs and availability.

5.2 Contributions

This study's scientific contributions are the development and validation of a novel mathematical model to solve the TAP problem by integrating two distinct scientific concepts,and consideration of all essential parameters to optimize the cost and availability of a complex system. It was seen that it is the first study that looks at the OEMs side task allocating and packing process to elaborate initial operator‘s maintenance plan.

It also evaluated important factors that influence the supportability performance of a complex system and introduced an initial conceptual model attempting for ensuring the resilience of complex systems throughout their respective life cycles by proactively updating the original plan with data gathered during the development and operation periods.

For the industry, this work contributes with a scientific model that can aid in the creation of an effective maintenance plan for complex systems that takes into account multiple aspects of operator maintenance strategy, thus contributing to improve the maturity and effectiveness of products supportability since the start of operation. In the operation phase, it can assist operators in their short and medium-term maintenance planning and activities sequencing. Therefore, helping to cover the identified gaps in the field of supportability

5.3 Proposal for Future Work

The primary objective of this study was to address the procedural challenges associated with Task Allocation and Packing process in the development phase. The operators utilize the generated maintenance plan as input for aircraft maintenance planning (AMP) or flight and maintenance planning (FMP). Integrating the existing technique with AMP or FMP would enhance the assistance for decision-making in operational scenarios.

This study also presented an preliminary investigation into the feasibility of updating all constants and component parameters by a methodical examination of maintenance records, with the aim of formulating a resilient maintenance strategy. Future study may employ novel methodologies to further explore the feasibility of updating all constants and item characteristics through a maintenance and failure history analysis conducted using suitable learning technologies.

Furthermore, the incorporation of the model with MSG-3 analysis would provide proactive data gathering and analysis. This, in conjunction with a machine learning mechanism, would allow for prompt and adaptable modifications to the product in the event that its performance fails to reach anticipated standards.

In summary, the maintenance researcher field should encompasses the following topics:

- Packaging model integration with flight and maintenance planning (FMP) and Aircrfat Maintenance (AMP) tools.
- Integration of the model with MSG-3 and Maintenance Task Analysis procedures to

enable data collecting and analysis for product development, with the goal of achieving agile and on-time adjustments in the product if it does not meet the desired performance.

- Intensification of research into machine learning technologies to improve the update process by learning from field maintenance data.

- Integrate the model with Prognostic Health Monitoring to assist operators with dynamic aircraft maintenance and flight planning decisions.

- Studies to explore the feasibility of integrating the TAPP solver with prescriptive maintenance models at the operation phase.

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7 Appendix A

7.1 Algorithms

7.1.1 The data initialization algorithm

Algorithm 1 initializes constants, loads sets from files and creates the set of work packages. All capitalized constants are considered of global scope, being available for the other algorithms without the need of passing them as arguments.

Algorithm 1 *Initialize()*

```
1: $Y \leftarrow 5$   ▷ 5, 10, 15 years or more
2: $Prof \leftarrow \{1,\ 2,\ 3\}$   ▷ the operational level
3: $HY \leftarrow \{750,\ 1500,\ 2500\}$   ▷ flight hours per year depending on the operational level
4: $H \leftarrow HY[Prof] \times Y$   ▷ Calculates the flight hour horizon
5: $OoPfactor \leftarrow \{1.0,\ 1.4,\ 1.8\}$   ▷ Out-of-Phase cost factor
6: $DOC \leftarrow 70,000.000$   ▷ Daily Opportunity Cost
7: $OHD \leftarrow \frac{H}{Y \times 365}$   ▷ Operating Hours per Day
8: $HOC \leftarrow \lfloor \frac{DOC}{OHD} \rfloor$   ▷ hourly Opportunity Cost
9: $CMCF \leftarrow 3.0$   ▷ Corrective Maintenance Cost Factor
10: $CMTF \leftarrow 1.2$   ▷ Corrective Maintenance Time Factor
11: $C,\ M,\ Z,\ P \leftarrow$ load sets from files
12: $STEP \leftarrow \min_{t=1}^{|C|}(lim_t)$
13: $OoPStep \leftarrow \frac{STEP}{10}$
14: $numStops \leftarrow \lceil \frac{H}{STEP} \rceil$
15: $S \leftarrow \{\}$   ▷ set of regular maintenance stoppages
16: $OoP \leftarrow \{\}$   ▷ set of out-of-phase maintenance stoppages
17: $numOoPsteps = \lceil \frac{STEP}{OHD} \rceil$   ▷ number of OoP steps in days
18: for $i \leftarrow 1$ to $numStops$
19:     $stop_i \leftarrow i \times STEP$
20:     $B^i \leftarrow \{\}$
21:     $stoppage \leftarrow (stop_i,\ dt_i \leftarrow 0,\ cost_i \leftarrow 0,\ B^i)$
22:     $S \leftarrow S \cup \{stoppage\}$
23:     for $p \leftarrow 1$ to $numOoPsteps - 1$   ▷ for each regular stoppage create a number of OoP stoppages
24:         $OoP \leftarrow OoP \cup \{stop_i + OHD * p\}$
25: return $C,\ M,\ Z,\ P,\ S,\ OP$
```

Line 6 initializes Daily Opportunity Cost constant DOC and line 7 the number of operating hours per day that may receive values according to the client aircraft exhaustion level selected. Line 8 initializes Hourly Opportunity Cost constant HOC.

The $CMCF$ (line 9) is a corrective factor applied to the preventive maintenance cost to predict the corrective cost in case some repair is made necessary. The same applies to the $CMTF$ to predict the corrective maintenance duration.

Line 11 loads data into components C, preparations P, and qualifications M and line 4 defines the packing horizon as a function of the maximum flight hour limit among components. Line 14 calculates the number of maintenance stoppages in this horizon. Lines 15 to 22 creates the set of maintenance work packages.

All constants referred to in this algorithm may be updated through a maintenance and failures history analysis made by appropriate machine learning tools, according to the dynamics of operations and scenario changing.

7.1.2 The main algorithm

In Algorithm 2, it is defined 2 resolution methods: (1) a simple heuristic (*Simple*) to emulate engineers' steps in manually solving the TAPP. This heuristic allocates tasks to work packages with the only concern being keeping components from flying after their due flight hour; and (2) it is used a MIP solver and a *First-Fit Decreasing* (FFD) approximation algorithm that handles the same issues as the engineers, but with an efficient account of resources per work package, where resources were not accounted more than once per work package; checks if the number and qualifications available attend tasks needs; and also, in the FFD phase, that incompatible and precedent tasks are not executed in the same *Bin*.

Algorithm 2 *Main()*

```
 1: $C,\ M,\ Z,\ P,\ S \leftarrow Initialize()$
 2: $methods \leftarrow \{Simple, ETAPPS\}$
 3: $useFFD \leftarrow \{False, True\}$
 4: $iter \leftarrow 20$        ▷ number of iteration to get the average test results, $iter \geq 1$
 5: $MC_{tot} \leftarrow 0$
 6: $DT_{tot} \leftarrow 0$
 7: for $method \in methods$
 8:     for $ffd \in useFFD$
 9:         for $it \leftarrow 1$ to $iter$
10:             $T \leftarrow CreateTasks(C,\ M,\ Z,\ P)$
11:             $MC,\ DT \leftarrow Solve(method,\ S,\ T,\ ffd,\ C)$
12:             $MC_{tot} \leftarrow MC_{tot} + MC$
13:             $DT_{tot} \leftarrow DT_{tot} + DT$
14:         $MC \leftarrow \frac{MC_{tot}}{iter}$        ▷ calculate the average cost
15:         $DT \leftarrow \frac{DT_{tot}}{iter}$
16:         $A \leftarrow \frac{H-DT}{H}$        ▷ calculate the availability
17:         print $method,\ ffd,\ MC,\ A$
```

It is important to emphasize that all constants referred to (initialized by Algorithm 1) are considered global scope. This is why they are not passed as function arguments. An exception occurs when some argument is changed locally. e.g., T and C in line 10.

Line 1 initializes all constants and sets referred to in this Algorithm (2), according to Algorithm 1.

To simulate cycles of plan, execute, and record maintenance, it is defined a number of iterations (line 4), that creates tasks and solves the TAPP as a means of exploring the emulated real world events. Each cycle is composed of many maintenance events (or work packages) sequentially executed in a time horizon.

Line 9 solves *iter* times with the same method and accumulates the maintenance costs MC_{tot} and the downtime DT_{tot}, to be divided by *iter* lately to calculate the averages.

Line 11 solves the TAPP with one of the methods, returning the maintenance costs MC and the downtime DT.

Line 17 for each method, prints the estimated total maintenance cost and availability for the planned horizon.

7.1.3 The Simple method for TAPP

Algorithm 3 *Simple(S, T, C STEP)*

```
1: $X_{ij} \leftarrow 0$, for $i \in \{1, 2, ..., |S|\}$, for $j \in \{1, 2, ..., |T|\}$
2: for $j \leftarrow 1$ to $|T|$
3:     $t \leftarrow cid_j$
4:     for $i \leftarrow 1$ to $|S|$
5:         $flyUntil = C[t]^{last} + C[t]^{lim}$
6:         if $stop_i <= flyUntil$ and $flyUntil < stop_i + STEP$
7:             $X_{ij} \leftarrow 1$
8:             $C[t]^{last} \leftarrow i$
9: Return $X_{ij}$
```

Some remarks on Algorithm 5:

In the line 1, the variables are initialized to the Simple method.

Line 5 computes the remaining number of hours to fly.

Line 6 is used to evaluate if an item is capable of flying up to the next stoppage.

If the next stoppage exceeds the task limit, Line 7 will allocate a task in the current stoppage.

7.1.4 The Problem Solver

Algorithm 4 *Solve(method, S, T)*

```
$MC, DT \leftarrow 0, 0$
$X_{ij} \leftarrow 0$, for $i \in \{1, 2, ..., |S|\}$, for $j \in \{1, 2, ..., |T|\}$
$O_{pj} \leftarrow 0$, for $p \in \{1, 2, ..., |O|\}$, for $j \in \{1, 2, ..., |T|\}$
$W_{jb} \leftarrow 0$, for $j \in \{1, 2, ..., |T|\}$, for $b \in \{1, 2, ..., |B^i|\}$, for $i \in \{1, 2, ..., |S|\}$
if $method = ETAPPS$
    $X_{ij},\ O_{pj} \leftarrow Branch\&Cut.minimize()$
if $method = Simple$
    $X_{ij} \leftarrow SimpleSolve(S,\ T)$
if $ffd = True$
    for $i \leftarrow 1$ to $|S|$
        $B^i \leftarrow FFD(i,\ X_{ij},\ T,\ M,\ Z)$
        for $bin \in B^i$
            $dt_{bin} \leftarrow 0$
            for $t_j \in bin$
                if $pmdt_j + cmdt_j > dt_{bin}$
                    $dt_{bin} \leftarrow pmdt_j + cmdt_j$
            $DT \leftarrow DT + dt_{bin}$
else
    $DT \leftarrow DT + pmdt_j + cmdt_j$
$preps_i \leftarrow \{\ \}$                              ▷ set of unique preparations for package $i$
for $i \leftarrow 1$ to $|S|$
    for $j \leftarrow 1$ to $|T|$
        if $X_{ij} = 1$
            $last_t \leftarrow stop_i$
            $MC \leftarrow MC + pmc_j + cmc_j$
        else if $O_{pj} = 1$
            $last_t \leftarrow stop_i$
            $MC \leftarrow MC + pmc_j + cmc_j$
    for $prep \in preps_j$
        if $prep \notin preps_i$                   ▷ guarantee that no preparation is duplicated
            $preps_i \leftarrow preps_i \cup prep$
            $MC \leftarrow MC + prep.cost$
            $DT \leftarrow DT + prep.dt$
$A \leftarrow \frac{H-DT}{H}$
Return $MC,\ DT$
```

Some remarks on Algorithm 4: In line 1, the variables for maintenance cost (MC) and downtime (DT) are initialized. Lines 2-4 initialize the decision variables. In line 6, the *CoIn-Or Branch & Cut* solves TAPP and returns variables X_{ij} and O_{pj} set. In line 11, the number of bins is minimized by the *First Fit Decrease (FFD)* method and returns variables W_{jb} set. In line 8, the *Simple* method solves TAPP and returns variables X_{ij} set. Lines 21-33 add subtask costs to the maintenance cost and totalize downtime. In line 34, the availability (A) is calculated. Line 35 returns the optimized maintenance cost and calculated availability.

7.1.5 The First-Fit Decreasing algorithm

Algorithm 5 places a special implementation of the *First-Fit Decreasing (FFD)* solution method for the *Bin Packing Problem.* It minimizes the number of tasks bins, minimizing the work package downtime.

(JOHNSON, 1973) investigates the *First-Fit Decreasing (FFD)* algorithm in this doctoral thesis, with the main result being a proof that the *FFD* for the bin packing problem never returns a solution that uses no more than ($11/9 \times OPT$) bins, where OPT is the optimal number of bins. Later, (JOHNSON; GAREY, 1985) propose a new version that returns a solution that uses no more than ($71/60 \times OPT$) bins.

Algorithm 5 $FFD(i,\ X_{ij},\ T,\ M,\ Z)$

```
 1: $reserved \leftarrow 0$
 2: $bins \leftarrow \{\}$
 3: $b \leftarrow 1$
 4: $Bin_b \leftarrow \{\}$
 5: $bins \leftarrow bins \cup \{Bin_b\}$
 6: $W \leftarrow [0]$                    ▷ a matrix with $|T|$ rows and $|T|$ columns
 7: **sort**$_{j=1}^{|T|}(nmec_j + Z[zone_j]^{limit},\ decreasing)$
 8: **for** $j \leftarrow 1$ **to** $|T|$
 9:     **if** $X_{ij} = 1$
10:         $NotIncluded \leftarrow$ **True**
11:         **for** $Bin_b \in bins$
12:             $needed \leftarrow reserved + nmec_j$
13:             **if** $W_{jb} = 0$ **and** $needed \leq M[qualif_j]^{available}$ **and** $needed \leq Z[zone_j]^{limit}$
14:                 **if** $W_{incompatible_j b} = 0$ **and** $j > startAfter_j$
15:                     $Bin_b \leftarrow Bin_b \cup \{t_j\}$
16:                     $reserved \leftarrow reserved + nmec_j$
17:                     $NotIncluded \leftarrow$ **False**
18:                     $W_{jb} \leftarrow 1$
19:                     **break**
20:         **if** $NotIncluded$
21:             $reserved \leftarrow 0$
22:             $b \leftarrow b + 1$
23:             $Bin_b \leftarrow \{\}$
24:             $Bin_b \leftarrow Bin_b \cup \{t_j\}$
25:             $bins \leftarrow bins \cup \{Bin_b\}$
26:             $W_{jb} \leftarrow 1$
27: **return** $bins$
```

Some remarks on Algorithm 5:

Line 7 sorts tasks by the decreasing order of mechanics need.

Lines 1 and 21 initialize the number of reserved mechanics of qualification r for the task, as it is the size a *Bin* of tasks.

In line 2 a bin for each mechanic qualification is created. This is necessary because each qualification has its available number of mechanics, that will be the size of each bin. Until line 5 $|M|$ sets with 1 empty bin each are initialized.

In line 9, it is checked if the task j is associated to the package i to try task inclusions in any bin.

From line 11 until 19 the set of existent bins is iterated in a try to include a task. From line 15 until 18, if the task inclusion is feasible, it is included in a bin and variable W_{jb} is set to indicate this inclusion. Also variable $reserved^r$ is updated for feasibility check on later inclusion tries.

From line 20 to 25, if no task is included, a new empty bin is created and inserted in the set of bins.

We conducted some preliminary tests by trying to fit 50 to 200 items in as few bins as possible, indicating that FFD was likely to obtain solutions optimal or very close for most of the tests.

7.1.6 The tasks creation algorithm

Algorithm 6 is used to create or complement tasks for tests purpose. It uses 3 types of random selections: (1) *RandomReal* which selects in a continuous range of real numbers, (2) *RandomInteger* that selects in a discrete range of integers, and (3) $RandomChoice(set,\ number)$ that selects elements from a set, where the second parameter is the number of elements to be chosen. Algorithm 6 creates a set of tasks based on the sets of preparations, components and qualifications.

Algorithm 6 *CreateTasks(C, M, Z, P)*

```
1: $T \leftarrow \{\}$
2: for $j \leftarrow 1$ to $|C|$
3:     $c \leftarrow C[j]$    ▷ c is a component
4:     $c.last \leftarrow 0$    ▷ reset the last component stoppage (flight hour)
5:     $R_{c.lim} \leftarrow e^{-(\frac{c.lim}{c.\eta})^{c.\beta}}$
6:     $pmdt_j \leftarrow c.dt \times (1.0 + RandomReal[-0.2, 0.2])$
7:     $mat_j \leftarrow c.mat \times (1.0 + RandomReal[-0.2, 0.2])$
8:     $qualif_j \leftarrow RandomInteger[1,\ |M|]$
9:     $nmec_j \leftarrow RandomInteger[1,\ M[qualif_j].available]$
10:    $pmc_j \leftarrow HOC \times pmdt_j + mat_j + nmec_j \times pmdt_j \times M[qualif_j].wage$
11:    $cmc_j \leftarrow (1 - R_{c.lim}) \times pmc_j \times CMCF$
12:    $cmdt_j \leftarrow (1 - R_{c.lim}) \times pmdt_j \times CMTF$
13:    $pmc_j \leftarrow R_{c.lim} \times pmc_j$
14:    $pmdt_j \leftarrow R_{c.lim} \times pmdt_j$
15:    $incompatible_j \leftarrow -1$    ▷ no incompatible task
16:    $startAfter_j \leftarrow -1$    ▷ no precedent task
17:    if $j \mod 30 = 0$    ▷ if the remainder is zero
18:        $incompatible_j \leftarrow RandomInteger[j - 30,\ j - 1]$    ▷ 1 of the last 29 tasks is incompatible with $j$
19:        $startAfter_j \leftarrow RandomInteger[j - 30,\ j - 1]$    ▷ $j$ must start after 1 of the last 29 tasks is finished
20:    $zone_j \leftarrow RandomInteger[1,\ |Z|]$
21:    $t_j \leftarrow (pmc_j, pmdt_j, cmc_j, cmdt_j, zone_j, qualif_j, nmec_j, preps_j, startAfter_j, incompatible_j)$
22:    $T \leftarrow T \cup \{t_j\}$
23: return $T$
```

In lines 6 and 7, downtime ($pmdt_j$) and costs with material (mat_j) are initialized with a random noise on the historical values from the component (dt_t and mat_t) to emulate the real world variations.

The expected task cost (pmc_j) is initialized in line 10 as a function of the Hourly Opportunity Cost, the expected downtime and costs with material.

Each task must not be executed concurrently with its incompatible or precedent tasks (if it has some). So, lines 17 to 19 randomly selects the incompatible and precedent tasks.

The last maintenance stoppage of this component is initialized in line 4. This value is updated along TAPP resolution to simulate a series of maintenance stoppages in a flight time horizon.

Finally, in line 22 this task vector is added to the set under assembly which is returned in line 23. Set C is also returned because parameter $last_t$ has been initialized.

FOLHA DE REGISTRO DO DOCUMENTO

1. CLASSIFICAÇÃO/TIPO	2. DATA	3. DOCUMENTO Nº	4. Nº DE PÁGINAS
TD	07 de maio de 2024	DCTA/ITA/TD-013/2024	147

5. TÍTULO E SUBTÍTULO:

An innovative method to solve the maintenance task allocation & packing problem

6. AUTOR(ES):

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7. INSTITUIÇÃO(ÕES)/ÓRGÃO(S) INTERNO(S)/DIVISÃO(ÕES):

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8. PALAVRAS-CHAVE SUGERIDAS PELO AUTOR:

Maintenance optimization; MSG-3 Analysis; Task allocation; Aircraft systems; Supportability

9. PALAVRAS-CHAVE RESULTANTES DE INDEXAÇÃO:

Manutenção de aeronaves; Alocação de recursos; Otimização; Análise de falhas; Manutenção preventiva; Consciência situacional; Controle de Processos; Indústria aeronáutica; Engenharia Aeronáutica.

10. APRESENTAÇÃO: (**X**) **Nacional** ( ) **Internacional**

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11. RESUMO:

Este estudo apresenta um método inovativo para resolver com eficiência o problema de alocação e empacotamento de tarefas de manutenção (TAP), contribuindo para o setor de aviação que recentemente fez grandes progressos em direção a um futuro sustentável. A integração dos princípios da indústria 4.0 com a utilização de materiais aeronáuticos mais sustentáveis e a implementação de novas tecnologias no projeto de sistemas, incluindo novos sistemas de propulsão, resultaram no desenvolvimento de aeronaves que são ao mesmo tempo mais eficientes e sustentáveis. Em relação aos aspectos de manutenção, a utilização de tecnologias disruptivas e a implementação das funcionalidades da manutenção digital permitem a análise de dados em tempo real, facilitando o monitoramento e predição da saúde do sistema, aumentando a eficácia da manutenção baseada em condições. Apesar dos avanços, a indústria aeronáutica continua a enfrentar desafios na área de suportabilidade. A manutenção é considerada um dos fatores estratégicos que contribuem para a alta produtividade e suportabilidade de um sistema complexo, sendo importante para garantir que o sistema seja capaz de operar com segurança e alto desempenho operacional ao menor custo possível. Ao planejar a manutenção se faz necessário garantir que a estratégia adotada atenda a esses objetivos. O método proposto visa resolver parte dos problemas encontrados no processo de desenvolvimento de planos de manutenção, onde a indústria perde uma parte do potencial de otimização ao desenvolver as estratégias de manutenção sem o suporte de modelos e ferramentas científicas. A abordagem leva em consideração, os limites de voo dos componentes, probabilidade de falhas, custos de manutenção preventiva e corretiva, custo de oportunidade devido à indisponibilidade da aeronave, economia devido à alocação inteligente de tarefas preparatórias, e o sequenciamento de execução das tarefas, com base no relacionamento entre as tarefas e limitações de recursos. O problema foi resolvido em 2 fases: primeiro, aloca-se tarefas aos pacotes de forma otimizada (minimizando o custo geral sem ultrapassar os limites de segurança) e então, para cada pacote de trabalho, agrupa-se as tarefas como um problema de empacotamento, organizando tarefas multidimensionais em caixas multidimensionais, de forma a minimizar o tempo de inatividade da aeronave. O modelo criado mudou a forma de como as tarefas são alocadas. O método de resolução do problema foi validado em várias instâncias de testes utilizando dados gerados sinteticamente a partir de informações estatísticas e registros reais de manutenção de componentes aeronáuticos. O método de modelagem e resolução do problema apresentou resultados excelentes no âmbito deste estudo. Obteve-se, uma melhor alocação e sequenciamento das tarefas, o que resultou em maiores taxas de disponibilidade e diminuição substancial dos custos totais de manutenção. Em termos de consciência situacional, o modelo proposto proporciona ao planejador a flexibilidade necessária para gerir melhor as restrições de recursos e, ao mesmo tempo, alcançar resultados ótimos.

12. GRAU DE SIGILO:

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