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

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Abstract

Purpose – This paper aims to explore the optimization process involved in the aircraft maintenance allocation and packing problem. The aircraft industry misses a part of the optimization potential while developing maintenance plans. This research provides the modeling foundation for the missing part considering the failure behavior of components, costs involved with all maintenance tasks and opportunity costs.
Design/methodology/approach – The study models the cost-effectiveness of support against the availability to come up with an optimization problem. The mathematical problem was solved with an exact algorithm. Experiments were performed with real field and synthetically generated data, to validate the correctness of the model and its potential to provide more accurate and better engineered maintenance plans.
Findings – The solution procedure provided excellent results 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.
Originality/value – This is an innovative research providing a state-of-the-art mathematical model and an algorithm for efficiently solving a task allocation and packing problem by incorporating components' due flight time, failure probability, task relationships, smart allocation of common preparation tasks, operational profile and resource limitations.

Keywords Maintenance optimization, MSG-3, Task allocation, Maintenance costs, Aircraft systems, Bin-packing, Branch and bound, First fit decreasing

Paper type Research paper

1. Introduction

Maintenance is regarded as one of the strategic factors that contribute to the high productivity of a complex system. It is also important to ensure the system safe operation at the lowest cost throughout its life cycle. As defined by Kinnison (2004), Maintenance is *the process of ensuring that a system continuously performs its intended function at the designed level of reliability and safety*. It includes all actions necessary for retaining a system or product in, or restoring it to, a desired operational state (Blanchard, 2004).

The preventive maintenance comprises all maintenance actions performed, at specified intervals, to retain a system in a specified operational condition. It covers, failure prevention, potential failure detection and failure findings tasks to prevent deterioration of the system inherent reliability (Airlines for America, 2015).

The corrective maintenance includes the actions necessary to clear the system failures identified either during the operation or preventive maintenance activities. The corrective maintenance usually is more expensive than the preventive one. 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.

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The preventive maintenance is an important factor that impacts the aircraft fleet availability necessary to the airline revenue, and avoids the consequences of failures that could impact aircraft safety and operational performance, influencing the cost and downtime (Smith and Hinchcliffe, 2003).

Complex systems must therefore perform planned preventive maintenance (PM) to minimize the chance of 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, operational performance and costs, among others. Those attributes are directly affected by PM strategies established during product development.

Executing required aircraft maintenance tasks is a critical challenge when planning operations on airline systems. Strategies for task execution range from attempting to control each task individually, using the time limit of task as the maximum period for completion, to allocating multiple maintenance tasks into packages to be completed together during a defined maintenance stoppage.

In the first case, the maintenance plan would prioritize the utmost safe use of each component limit within a system, preventing the loss of useable hours. Nevertheless, the maintenance plan must establish an individual control of item preventive maintenance tasks. Due to the probabilistic nature of the failure, one may be more susceptible to failures occurring at inconvenient times, which may result in a rise in unavailability and associated costs. The second alternative, known as packing, generates less working packages and necessitates a relatively longer aircraft downtime. However, it allows for improved planning of activities and resources, as well as a reduced risk of additional downtime for modifications resulting from Service Bulletins, Airworthiness Directives and repairs.

Each of these strategies has cost components associated: the cost of lost income due to aircraft stoppage, the cost of unused flight hour; the cost of preventive maintenance and probability cost of corrective maintenance. The possible PM plan minimizes costs through a proper combination of these costs.

The problem is that maintenance planning is conservative due to limitations faced by maintenance engineers, such as the absence of efficient tools to support the MSG-3 analysis (Airlines for America, 2015; Ahmadi *et al.*, 2010; Liu *et al.*, 2006), and the allocation of tasks during the design of the operator's maintenance plan. It is desirable that the organization of tasks into packages considers all the relevant aspects of operation and maintenance in a way to minimize the total maintenance costs, maximizes fleet availability and facilitates flight operations and maintenance planning.

The initial maintenance requirements for a commercial aircraft are derived from the type certification (TC) and the Maintenance Review Board (MRB) processes (Federal Aviation Administration, 2012). Figure 1 depicts the information flow used to produce the initial maintenance requirements and assign them to the appropriate maintenance packages.

Dependability data is used in both analyses, as well as in the Task Allocation process, which is concerned with the arrangement of the resulting maintenance requirements.

The requirements originated by the TC process aim to keep the inherent safety level defined by the type design. These requirements are considered limitations and are derived from different safety analysis required for certification.

Through the MRB process, manufacturers, regulatory authorities, vendors and operators together develop the initial scheduled maintenance requirements for the aircraft. The global aeronautical industry uses the MSG-3 methodology (Airlines for America, 2015) to define the maintenance tasks. This methodology is the result of a collaborative effort by of manufacturers, operators and authorities, who convened regularly to develop it.

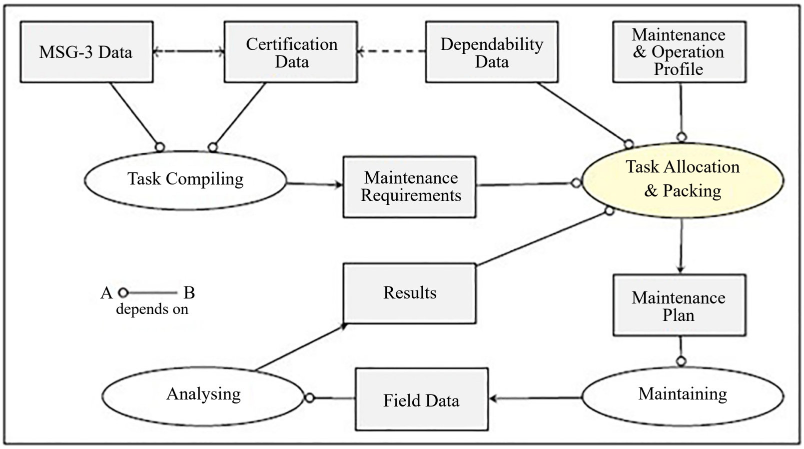


Figure 1.
Maintenance plan development

Source(s): Authors

The resulting scheduled tasks are published in the OEM's Maintenance Planning Data (MPD) document, which contains also essential planning information organized over many document sections in accordance with the iSpec 2200 standard (Arlines for America, 2000). Task intervals is depicted in flight hours, flight cycles, landings or calendar-based, according to their governing usage parameter. MPD annexes may contain OEM package suggestion.

Besides the requirements from MSG-3, certification and MPD, the task allocation process depends on the dependability data, and aircraft expected operation and maintenance profile.

Kinnison (2004) highlights that maintenance is designed to maintain or restore the asset's reliability to its design-in level. Noteworthy is the role that effective maintenance can play in attaining the desired levels of availability, as it can preserve the inherent reliability and reduce the repair time. The optimal maintenance strategy for a component or a multi-component system can significantly influence minimizing costs and downtime (Rebaiaia and Ait-kadi, 2021). This strategy is determined by the parameters of the component time-to-failure distribution, the costs of PM and the costs associated with the failure. Thus, the final maintenance plan is influenced by the predicted system reliability and ease of repair that is a maintainability characteristics.

An effective PM, scheduled or prognosis based, prevents failures that need costly corrective maintenance, and would cause flight cancellations or delays, affecting the airline network's schedule and profitability.

The actual cost of an Aircraft On Ground (AOG), a condition in which an aircraft has a failure that prevents it from flying (Pereira Barreto *et al.*, 2021), numerous factors must be considered, including location, parts availability and the availability of qualified mechanics.

In summary, an inefficient and suboptimal preventive maintenance program can affect the stakeholders in terms of operational availability and costs; disruption of the flight network; investment return; future sales and the aircraft reputation.

This study extends complex system maintenance research by providing a new model to allocate tasks in packages aiming to assure the aircraft operating capability and safety, in a cost-effective manner.

This paper is organized as follows: the review of literature regarding the packing problem is presented in section 2. Problem definition and specification are presented in section 3.

TAP details and formulation are presented in section 4. The solution method and algorithms are described in the chapter 5, while the results are explained in section 6 and conclusion on section 7.

2. Literature review

Early studies on optimization focus on only the system maintenance cost rate, excluding the other system performance indicators (Sharma *et al.*, 2011). Nevertheless, the goal of maintenance optimization studies is to reduce total system expenses while increasing system availability by the implementation of optimal maintenance policies and inspection intervals.

Maintenance optimization studies can be classified into three categories: task interval definition, maintenance planning and task allocation.

2.1 Task interval definition

Ahmadi and Kumar (2011) modeled a Cost Rate Function that utilizes mean fractional dead time concept to define a maintenance policy for an aging item prone to a hidden failure. They evaluate costs of performing a restoration task, a failure finding inspection or both. Lienhardt *et al.* (2012) presented a similar study employing semi-Markov chain to calculate the system steady-steady availability and the cost rate, in function of the maintenance interval. Bozoudis *et al.* (2018) proposed a maintenance planning optimization tool that considers the functional reliability diagram, importance assigned to each item and costs. The software identifies the best maintenance cost-to-reliability ratio point, to define the most appropriated maintenance.

2.2 Maintenance planning

Abrahão and Gualda (2006) developed a model to optimize fleet PM programming using a hybrid ant colony optimization meta-heuristic. They consider the flight programming, aircraft remaining hours and maintenance shop availability to decide when and which aircraft should be removed from operation to the maintenance. Gavranis and Kozanidis (2015) modeled a Flight and Maintenance plan problem, and use a precise algorithm to decide which available aircraft should fly, for how long and on which aircraft maintenance should be performed to maximize the availability. Shah *et al.* (2017) presented a similar study to optimize the maintenance plan of a military fleet using multi-integer linear programming. It aims to optimize the operational readiness. Balakrishnan *et al.* (2021) created a model that employs a metaheuristics to optimize fleet utilization. They employed Genetic Algorithm and a modified Honeybee metaheuristics to strategize fleet usage and maintenance stoppages to optimize the aircraft utilization rate. Deng *et al.* (2021) created a system aiming improving the maintenance check schedule. Initially, an algorithm examines the period selected by the user for each inspection category. Then, the period is divided into discrete intervals (bins). A heuristic algorithm assigns tasks to the suitable bins, considering the capacity of hangar, task frequency and the urgency in finishing the tasks.

2.3 Task allocation

The following investigations address the optimization of maintenance task allocation providing the best distribution of tasks into packages. They are directly relevant to the study detailed in this paper.

Muchiri and Klaas (2009) proposed a strategy for arranging tasks into manageable packages for base or line maintenances. The authors suggest an initial interval de-escalation to manage packages inside their limits. The model tackles seasonal aircraft usage and operating circumstances. The proposed Maintenance Item Allocation Model simulates aircraft utilization, plans due maintenance under different scenarios, and clusters tasks. Seasonal utilization improves the effectiveness of operational profile consideration. The interval de-escalation technique is also employed by Witteman *et al.* (2021), but incorporating a penalty according to the de-escalation length. Hölzel *et al.* (2012) also considers task clustering to optimize maintenance scheduling. In this case, authors use the branch-and-bound technique, like Hölzel *et al.* (2012), Lee *et al.* (2022) and Si *et al.* (2023) to solve this NP-Hard problem, and efficiently handle task allocations. They organize the task or tasks (clustering) using the single-task oriented approach, considering the resources available, task limits and the time when the aircraft is on the ground. Although presenting greater administrative complexity, the single-task oriented concept is also adopted by Senturk and Ozkol (2018), Silva *et al.* (2023). Li *et al.* (2015) research focused on testing the performance of a novel simplex algorithm in optimizing maintenance costs. The algorithm is developed to equalize an A-check into numerous smaller packages that can be done overnight at line maintenance. They suggested an improved fuzzy C-means clustering model to combine maintenance tasks. In addition to task intervals, the model considers the relationships between tasks, concerning the systems (ATA code), task type and aircraft zones where the tasks will be performed. Equalizations can prevent a sudden increase in demand on maintenance resources, but it requires more rigorous administration of maintenance activities. The task relationship is also considered by Si *et al.* (2023), but differently from Li *et al.* (2015) they consider only the zones where tasks will be conducted as a relationship factor. Senturk and Ozkol (2018) suggested de-packing and a single-task control of A and C check maintenance requirements, attempting to reduce airplane maintenance downtime. A software to re-include tasks in packages based on aircraft utilization is proposed. The software considers, task intervals, utilization characteristics and required resources. However, it lacks the packing benefits that arise from sharing similar preparatory procedures (Si *et al.*, 2023; Lee *et al.*, 2022). Address this packing factor that has the potential to improve the accuracy of cost-benefit analysis. Witteman *et al.* (2021) provided a solution for the multi-year task allocation problem for an aircraft fleet. They handle airline packing and unpacking process, with the objective of assisting operators to keep their fleets flying. Authors also proposed a de-escalation with a cost charge based on de-escalation length. They formulate this problem as a time-constrained variable-sized bin packing problem by adding deadlines, intervals and arrivals for the recurring tasks. It is proposed a constructive heuristic based on the worst-fit decreasing algorithm. Like Deng *et al.* (2021), the time horizon is divided into maintenance segments for each aircraft, treated as bins with specific durations in days and limited by the available resources. The study provides significant contributions for resolving the task allocation problem. Lee *et al.* (2022) proposed the integration of remaining useful life (RUL) prognostics of a PHM capable system with a maintenance planning framework. It determines the best braking system opportunistic maintenance plan for landing gear brakes using RUL prognostics generated by a Bayesian regression model. A mixed-linear integer programming solver integrates prognostic tool outputs with scheduled and unscheduled replacement costs. Furthermore, the solution assesses the RUL of components, scheduled maintenance time slots and the availability of hangar resources. The model targets the landing gear brakes maintenance and examines the benefits of replacing multiple items at the same maintenance stoppage. Si *et al.* (2023) proposal for maintenance packing and task allocation strategies, includes maintenance cost metrics, failure characteristics and an operator-defined risk value, based on failure relevance. The optimal packaging is decided based on the overlapping of useable intervals, resource restrictions, task correlation, determined by the zones accessed, and the user's tolerance for corrective maintenance. The cost rate is established by the estimated cost of unit downtime and the average time of operation. The authors include the cost of predicted number of failures in addition to preventative maintenance costs, which some studies have overlooked. Silva *et al.* (2023) proposed the implementation of a maintenance scheduling framework using a static algorithm that produces the initial plan and, an adaptive algorithm that utilizes the reinforcement learning mechanism to update the plan. The optimization utilizes three key performance indicators: time slack, measure of the time distance from the due date, also considered by

Muchiri and Klass (2009) and Senturk and Ozkol (2018), ground time, that is the period that the aircraft is not flying, and change score, reflecting the extent of changes need. Like Senturk and Ozkol (2018), they also consider the de-packaging of tasks. Each task can be assigned in a normal check, or any small stoppage based on solver analysis.

2.4 Contribution of this research

The study in this paper proposes an innovative model to efficiently solve a TAPP problem building the initial maintenance plan for the aircraft entry to service, by incorporating important factors: task relationships; savings from sharing common preparation tasks; expected number of failure between preventive maintenance, also used by Si *et al.* (2023) and partially by Lee *et al.* (2022), opportunity cost due to maintenance downtime addressed by Si *et al.* (2023) and indirectly by Li *et al.* (2015) and Hölzel *et al.* (2012), operational profile, also used by Muchiri and Klaas (2009), Senturk and Ozkol (2018), Lee *et al.* (2022), Silva *et al.* (2023), resources available and zone limits, that are covered indirectly by Si *et al.* (2023) and Li *et al.* (2015), and efficient and strategic arrangement of tasks inside a package according to task relationships, zones and availability of resources.

3. Problem formulation

3.1 Problem specification and analysis

Task allocation is inefficient because maintenance plan engineers use, in the majority of cases, only their experience instead of a scientific method support. Task intervals, material, man-hour and access are usually considered. However, the packing is not optimal, since it does not account expenses of corrective actions based on item failure probabilities, production losses and savings from packing tasks that share preparations.

The problem consists in allocating maintenance tasks, which are defined at different intervals in packages. The goal is to define the best allocations for task tj into the existent packages |S|, as shown in Figure 2, to minimize costs and improve availability.

Although task packing is desirable, some tasks are expected to be planned as *Out Of Phase* (*OOP*), outside of a regular package.

3.2 Problem summary

The problem can be summarized as to optimally allocating tasks to packages in a way to minimize costs and downtime. It focuses on the final steps of the product development phase and does not address the flight and maintenance planning that occurs during the operation phase. Nonetheless, the proposed approach can assist in revising medium and long-term operator's planning.

An effective optimization model must considers the following data and premises: task information resulting from MSG-3 and certification process; dependability data; costs of maintenance tasks and production loss due to downtime; the components probability of failure; components task intervals; costs of repair; expenses due to network disruption, such passenger accommodations and meals; and savings of packing tasks that share the same preparation resources.

We resolve this problem by first optimally allocating tasks to packages (guaranteeing that the overall cost is minimized); and then, for each package, grouping tasks as a Bin Packing Problem by arranging multidimensional tasks into multidimensional bins, in a way to minimize downtimes.

As we changed the way tasks are better allocated to packages by packing them into time bins, we introduce the Task Allocation and Packing Problem (TAPP), which is target of this work.

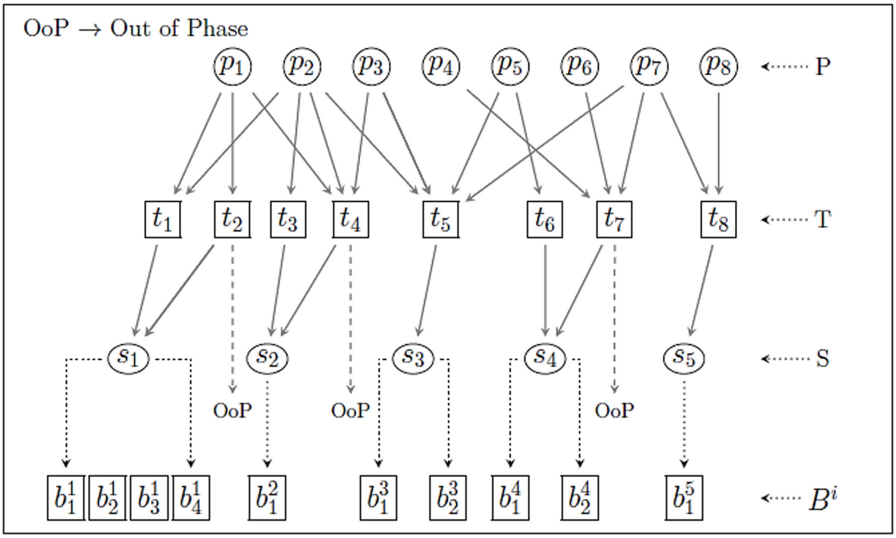


Figure 2.
Task allocation and packing

Source(s): Authors

4. Methodology and modeling

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

Let $C = \{c_1, c_2, c_3, \ldots, c_{|C|}\}$ be a set of aircraft components, 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); Task intervals are defined based on the item's predominant utilization parameter.

Let M = {General, Airframe, Powerplant, Avionics, Inspection} be a set of aviation mechanics with the following attributes: qualifications ($qualif_r$), number of available ($available_r$) mechanics for each technical qualification. Each qualification ($qualif_r$) has the attribute $wager_r$ expressed in US$/h.

Let Z = {z1, z2, z3, . . ., z|Z|} be a set of aircraft zones according to the ATA-100 Specification, 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 areas of an aircraft that identify where maintenance activities occur.

Let $P = \{p_1, p_2, p_3, \ldots, p_{|P|}\}$ be a set of maintenance preparations tasks, that must be performed before or after a maintenance task, to be efficiently allocated with the task to the set of packages.

Each preparation p_k has the attributes:

(1) $name_k$ (a defining name for preparation);

(2) $cos\,t_k$ (preparation p_k overall cost);

(3) mh_k (estimated preparation p_k man-hours);

(4) $qualif_k$ (mechanic qualification needed);

(5) $qualif_k^r$ (numbers of mechanics for each qualification needed to execute the preparation task p_k);

(6) $nmec_k$ (number of mechanics needed).

(7) dt_k (estimated preparation p_k downtime);

The cost for each preparation task p_k is calculated through Equation (1).

$$\cos t_k = \left[\sum_{r=1}^{|M|} mh_k^r \times wage^{qualif_k^r} + mat_k\right] + \left[\sum_{r=1}^{|M|} \frac{mh_k^r}{nmec_k^r} \times HOC\right] \text{for } k\,\{1,2,3,\ldots,|P|\} \quad (1)$$

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 of mechanics necessary to accomplish the preparation p_k,

Let $T = \{t_1, t_2, t_3, \ldots, t_{|T|}\}$ be a set of maintenance tasks to be allocated to the one of packages. Each task t, has the following attributes:

(1) cid_j (component`s identifier)

(2) lim_j (time limit to accomplished task t_j);

(3) $last_j$ (time of the last execution of task t_j);

(4) pmc_j (PM cost of t_j);

(5) $pmdt_j$ (PM downtime of t_j);

(6) $pmoc_j$ (PM opportunity cost associated to $pmdt_j$);

(7) cmc_j (CM cost associate to corrective maintenance of t_j);

(8) $cmdt_j$ (CM downtime associated to t_j);

(9) $cmoc_j$ (CM opportunity cost associated to $cmdt_j$);

(10) $znum^{xr}$ (Number of mechanics of each qualification $qualif_r$ needed for task t_j to be executed in zone z_x);

(11) $zone_j$ (zones accessed during the task execution);

(12) $nmec_r$ (number of mechanics of qualification ($qualif_r$) needed);

(13) $preps_j$ (list of preparations necessary to accomplished task t_j);

A task t_j may be subject to certain constraints if 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. In this study we use 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.

Equation (2) represents the reliability of component c_t included in task t_j, if task is planned to stoppage s_i with interval $stop_i$, while equation (3) gives the reliability if the task is considered to *out-of-phase* stoppage o_p:

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

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

Let A_j be a set of P containing the preparations necessary to task t_j.

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

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

The preparations included in package s_i with n_i tasks, is defined by $P_i = \{q_1, q_2, q_3, \ldots, q_{|Pi|}\}$, as shown in equation (4):

$$P_i = \bigcup_{j=1}^{n_i} C_{ij} \tag{4}$$

The preventive maintenance cost related to labor and material for each task t_j is calculate through Equation (5).

$$\text{pmc}_j = \left[\sum_{r=1}^{|M|} mh_j^r \times wage^r + mat_j \right] \text{for j} \in \{1, 2, \ldots, |T|, \text{for r} \in \{1, 2, 3, \ldots, |M| \tag{5}$$

The preventive maintenance opportunity cost for each task tj is calculated through Equation (6).

$$\text{pmoc}_j = \left[\sum_{r=1}^{|M|} \frac{mh_j^r}{nmec_j^r} \times HOC \right] \text{for j} \in \{1, 2, \ldots, |T|, \text{for r} \in \{1, 2, 3, \ldots, |M| \tag{6}$$

Equations (7) through (8) give the task t_j inherent corrective maintenance (CM) cost calculations: The corrective maintenance labor and material cost for each task t_j is:

$$\text{cmc}_j = \left[\sum_{r=1}^{|M|} mh_j^r \times CMCF \times wage^r + mat_j \right] \text{for j} \in \{1, 2, 3, \ldots, |T|\} \text{for } r \in \{1, 2, 3 \ldots, |M|\} \tag{7}$$

The corrective maintenance opportunity cost for each task t_j is:

$$\text{cmoc}_j = \left[\sum_{r=1}^{|M|} \frac{mh_j^r}{nmec_j^r} \times CMTF \times HOC \right] \text{for } j \in \{1, 2, 3, \ldots, |T|\}, \text{for } r \in \{1, 2, 3 \ldots, |M|\} \tag{8}$$

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, mh^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.

Let $S = \{s1, s2, s3, \ldots, s|S|\}$ be a set of maintenance work packages, each with the attribute $stop_i$, the maintenance stoppage interval and parameters to be updated after optimization: $cost_i$ (overall work package maintenance cost); dt_i (overall work package maintenance downtime); n_i (number of tasks included in the package) and $preps_i$ (the set of unique subtasks associated to the package).

Let $O = \{o1, o2, o3, \ldots, o|O|\}$ be a set of Out of Phase (O_P) stoppages 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 cannot be allocated to s_{i+1} because the item would fly after its due limit.

Let $B_i = \{b_1^i, b_2^i, b_3^i, \ldots, b_{|B^i|}^i\}$ be a set of maintenance bins which are partitions of maintenance work packages |B|, as showed in Figure 3 for example, 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*.

Regarding the *Bin* downtime (dt^i), it may be accounted as the longest task, and the overall bins downtime may be reduced by minimizing the number of bins.

In general, the task constraints related to tasks in the same Bin would be implemented; in this work, only the $startAfter_j$ and $incompatible_j$ constraints are managed, as the referred task must be in one of the previous bins and incompatible tasks must not be in the same bin.

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

We define 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 and its preparations $preps_j$, not included in the regular packages, to out-of-phase stoppage o_p; (3) W_{jb} to assign task t_j to bin b_b.

(1) The binary variables $X_{ij} = 1$ if task t_j is assigned to maintenance package s_i, and 0 otherwise.

(2) The binary variables $O_{pj} = 1$ if task tj is assigned to an out-of-phase stoppage, and 0 otherwise.

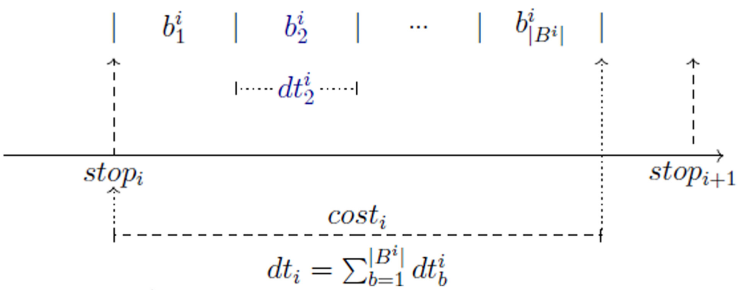
(3) The binary variables $W_{jb} = 1$ if task t_j is allocated to the bin b_b, and 0 otherwise.

Equation (9) corresponds to the regular package preventive maintenance costs parcel, including the amount relative to the preparation's costs after respective savings.

$$\text{pmc}_j^i = R_t^i \times \left[(pmc_j + pmoc_j) + \sum_{q=1}^{n(P_i)} prepc_q \right] \tag{9}$$

Equation (10) corresponds to the expected corrective maintenance costs if task t_j is included in the regular package s_i

$$\text{cmc}_j^i = 1 - R_t^i \times [(cmc_j + cmoc_j)] \tag{10}$$



Source(s): Authors

Figure 3.
Work package bins

Equation (11) corresponds to the *out-of-phase* stoppage preventive maintenance cost. In this case, there is no savings as regarding the preparations.

$$\mathrm{pmc}_j^p = R_t^p \times \left[(pmc_j + pmoc_j) + \sum_{q=1}^{n(A_j)} prepc_q \right] \tag{11}$$

Equation (12) corresponds to the expected corrective maintenance costs if task t_j is included in the out-of-phase stoppage o_p.

$$\mathrm{cmc}_j^p = 1 - R_t^p \times [(cmc_j + cmoc_j)] \tag{12}$$

Equations (13) and (14) calculate the flight hour unused factor for both tasks allocated in regular package and out-of-phase tasks respectively, that is, how much flight hours the aircraft did not fly for being stopped before its flight limit.

$$\mathrm{unusedP}_i^j = \left\lceil \frac{stop_i}{lim_j + last_j} \right\rceil - \frac{stop_i}{lim_j + last_j}, \mathrm{for\, j} \in \{1,2,3,\ldots,|T|\}, \mathrm{for\, i} \in \{1,2,3,\ldots,|S|\} \tag{13}$$

$$\mathrm{unusedO}_p^j = \left\lceil \frac{stop_p}{lim_j + last_j} \right\rceil - \frac{stop_p}{lim_j + last_j}, \mathrm{for\, j} \in \{1,2,3,\ldots,|T|\}, \mathrm{for\, p} \in \{1,2,3,\ldots,|O|\} \tag{14}$$

Equation (15) states the first Objective Function that minimizes the maintenance cost of all tasks $|T|$ and preparation $|P|$ in the defined horizon $|S|$ if tasks and preparations are allocated to work packages. It also attempts to minimize the unused hours costs.

$$\begin{aligned} min \Bigg\{ & \left[\sum_{i=1}^{|S|} \sum_{j=1}^{|T|} X_{ij} * \left(cmp_j^i + cmc_j^i + unusedP_i^j \times (pmoc_j + pmc_j) \right) \right] \\ & + \left[\sum_{p=1}^{|O|} \sum_{j=1}^{|T|} O_{pj} * \left(cmp_j^p + cmc_j^p + unusedP_p^j \times (pmoc_j + pmc_j) \right) \right] \Bigg\} \end{aligned} \tag{15}$$

Subject to:

$$X_{ij} \times unusedP_i^j \geq 0, for\, j \in \{1,2,3,\ldots,|T|\}\, and\, for\, i \in \{1,2,3,\ldots,|S|\} \tag{16}$$

$$O_{pj} \times unusedO_p^j \geq 0, \mathrm{for\ j} \in \{1,2,3,\ldots,|T|\}\ \mathrm{and\ for\ p} \in \{1,2,3,\ldots,|O|\} \tag{17}$$

Equations (16) and (17) hinder a component from flying beyond its time limit.

$$\sum_{i=1}^{|S|} X_{ij} + \sum_{p=1}^{|O|} O_{pj} \geq \left\lfloor \frac{stop_{|S|}}{lim_j} \right\rfloor, \mathrm{for}\, j \in \{1,2,\ldots,|T|\} \tag{18}$$

Equation (18) guarantees that the task t_j is executed at least $\left\lfloor \frac{stop_{|S|}}{lim_j} \right\rfloor$ times.

$$last_t = \mathrm{last_t} \times (1 - X_{aj}) + \mathrm{stop}_a \times X_{aj}, \mathrm{for\ each}\ t \in \{1,2,\ldots,|C|\} \tag{19}$$

For $i \in \{1, 2, \ldots, |S|\}$, $a \in \{1, 2, \ldots, i-1\}$, the last component stoppage is calculated (Equation 19).

$$\sum_{k=1}^{|P|} |B_i| = X_{ij} \tag{20}$$

For $i \in \{1, 2, \ldots, |S|\}$, $k \in \{1, 2, \ldots, |P|\}$, if the task is associated to the work package ($X_{ij} = 1$), the preparation p_k will be unique (Equation 20), that is the same door will not open or closed more than once.

$$\sum_{r=1}^{|M|} \sum_{x=1}^{|Z|} X_{ij} \times znum_j^{xr} > 0, \text{or ach} \in \{1, 2, \ldots, |T|\} \tag{21}$$

For $x \in \{1, 2, \ldots, |Z|\}$ and $i \in \{1, 2, \ldots, |S|\}$, the amount of mechanics of task zones must be greater than zero or the task will not be included (Equation 21).

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

$$\text{minimize} \left|B^i\right| \tag{22}$$

Equation (22) states the second Objective Function that minimizes the number of bins. This minimizes the overall downtime.

Subject to:

$$\sum_{b=1}^{\left|B^i\right|} W_{jb} = 1, \text{for each i} \in \{1, 2, \ldots, |T|\} \tag{23}$$

Each task must be in exactly one Bin, if associated to the Bin (Equation 23).

$$\sum_{j=1}^{|T|} \sum_{r=1}^{|M|} W_{jb} \times znum_j^{xr} \leq limit_x \tag{24}$$

For each $b \in \{1, 2, \ldots, |B_i|\}$ and for each $x \in \{1, 2, \ldots, |Z|\}$, the number of mechanics cannot exceed the zone limit (Equation 24).

$$\sum_{j=1}^{|T|} \sum_{x=1}^{|Z|} W_{jb} \times znum_j^{xr} \leq available_r \tag{25}$$

For each $b \in \{1, 2, \ldots, |Bi|\}$ and for each $r \in \{1, 2, \ldots, |M|\}$, the number of mechanics cannot exceed the available for each qualification (Equation 25).

$$W_{t1,b1} \times b1 < W_{t2,b2} \times b2, for\,(b1, b2) \in \left\{1, 2, 3, \ldots, \left|B^i\right|\right\}, for\,(t1, t2) \in \{1, 2, 3, \ldots, |T|\} \tag{26}$$

Equation (26) guarantees that task t_2 will be put in bin b_2, which is posterior to bin b_1 because task t_2 must start after t_1 is finished ($t_1 = StartAftert_2$).

$$X_{ic}^b = 1 - X_{id}^b \tag{27}$$

For $c, d \in \{1, 2, \ldots, |T|\}$, $i \in \{1, 2, \ldots, |S|\}$, and $b \in \{1, 2, \ldots, |Bi|\}$; and for $c \in incompatible_d$ or $d \in incompatible_c$, as c and d are segregated tasks, Equation (27) guarantees that they will not be executed in the same bin.

5. Solution strategy and algorithms

The resolution strategy considered the cost optimization by means of Efficient Task Allocation and Packing Problem Solver (ETTAPS), and availability optimization using the First-Fit Decreasing (FFD) algorithm.

The complete algorithm set is available at https://www.aerologlab.ita.br/datafiles/. The primary algorithms are described below:

5.1 The main algorithm

We define 2 solution 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) we 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; 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.

Main *(S, T, C)*

$C, M, Z, P, S \leftarrow Initialize()$

$methods \leftarrow \{Simple, ETAPPS\}$

$useFFD \leftarrow \{False, True\}$

$iter \leftarrow 20$

$MC_{tot} \leftarrow 0$

$DT_{tot} \leftarrow 0$

for $method \in methods$

  for $ffd \in useFFD$

    for $it \leftarrow 1$ **to** $iter$

    $T \leftarrow CreateTasks(C, M, Z, P)$ — read the MPD information

    $MC, DT \leftarrow Solve(method, S, T, ffd, C)$

    $MC_{tot} \leftarrow MC_{tot} + MC$

    $DT_{tot} \leftarrow DT_{tot} + DT$

    $MC \leftarrow \frac{MC_{tot}}{iter}$ — average cost

  $DT \leftarrow \frac{DT_{tot}}{H}$ — average downtime

  $A \leftarrow \frac{H-DT}{H}$ — availability

It is important to emphasize that all constants are considered global scope. This is why they are not passed as function arguments. An exception occurs when some argument is changed locally, for example T and C in line 10.

To simulate cycles of plan, we defined a number of iterations (line 4), that updates tasks and solves the TAPP as a means of exploring the emulated real-world events.

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 costs MC and downtime DT.

5.2 The simple method for TAPP

The Simple algorithm allocates tasks based only in the maximum allowable interval of tasks.

Simple(*S, T, C*)

```
1: X_ij ← 0, for i ∈{1, 2, ..., |S|}, for j ∈{1, 2, ..., |T|}
2: for j ← 1 to |T|
3:     t ← cid_j
4:     for i ← 1 to |S|
5:         flyUntil = C[t]^last + C[t]^lim        . calculate the available hours of component.
6:         if stop_i <= flyUntil and flyUntil < stop_i + STEP        . allocate task if next stop is not feasible.
7:             X_ij ← 1
8:             C[t]^last ← i
9: Return X_ij
```

5.3 The first-fit decreasing algorithm

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

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

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: j=1 **sort**$^{|T|}$ $(nmec_j + Z[zone_j]^{limit},\ decreasing)$
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** $W_{incompatible\ b} = 0$ **and** $j >_i startAfter_j$
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** $bins$

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

Lines 1 and 21 initialize the number of reserved mechanics of qualification $qualif_r$ 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 t_j is associated to the package s_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.

5.4 The problem solving algorithm

Solve(*method, S, T*)

```
1: MC, DT ← 0
2: X_ij ← 0, for i ∈{1, 2, ..., |S|}, for j ∈{1, 2, ..., |T|}
3: O_pj ← 0, for p ∈{1, 2, ..., |O|}, for j ∈{1, 2, ..., |T|}
4: W_jb ← 0, for j ∈{1, 2, ..., |T|}, for b ∈{1, 2, ..., |B^i|}, for i ∈{1, 2, ..., |S|}
5: if method = ETAPPS
6:     X_ij, O_pj ← Branch&Cut.minimize()
7: if method = Simple
8:     X_ij ← SimpleSolve(S, T)
9: if ffd = True
10:     for i ← 1 to |S|
11:         B^i ← FFD(i, X_ij, T, M, Z)
12:         for bin ∈ B^i
13:             dt_bin ← 0
14:             for t_j ∈ bin
15:                 if pmdt_j + cmdt_j > dt_bin
16:                     dt_bin ← pmdt_j + cmdt_j
17:             DT ← DT + dt_bin
18: else
19:     DT ← DT + pmdt_j + cmdt_j
    State preps_i ← { } .                      set of unique preparations for package i
20: for i ← 1 to |S|
21:     for j ← 1 to |T|
22:         if X_ij = 1
23:             last_t ← stop_i
24:             MC ← MC + pmc_j + cmc_j
25:         else if O_pj = 1
26:             last_t ← stop_i
27:             MC ← MC + pmc_j + cmc_j
28:     for prep ∈ preps_j
29:         if prep /∈ preps_i                 . guarantee that no preparation is duplicated
30:             preps_i ← preps_i ∪ prep
31:             MC ← MC + prep.cost
32:             DT ← DT + prep.dt
33:     A ← (H − DT) / H
34: Return MC, D
```

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 and Cut* solves TAPP and returns variables X_{ij} and O_{pj} set.

In line 8, the Simple method solves TAPP and returns variables X_{ij} set. In line 11, the number of bins is minimized by the First Fit Decrease (FFD) method and returns variables Wjb set.

Lines 20–32 add subtask costs to the maintenance cost and totalize downtime. In line 33, the availability (A) is calculated.

Line 34 returns the optimized maintenance cost and availability.

6. Results and discussion

We use the Branch-and-Cut method to resolve this work's problem. The version of MIP solver we use is the *CoIN–OR CBC* developed by Forrest *et al.* (2020) and maintained by a small group of volunteers under the auspices of the non-profit COIN–OR Foundation (www.coin-or.org/Cbc).

To enhance the gains in the availability, we implement the use of the First-Fit Decreasing that 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 case study is based on the following assumptions:

(1) The tasks interval considered a hard constraint.

(2) Items can show a constant or increasing failure rate characteristics.

(3) Items are subject to perfect maintenance.

(4) Components subject to repair or restoration are considered as good as new (AGAN) after maintenance.

(5) Interval changes on degradation finding tasks (Inspections or Functional Checks) may require adjustments on their test parameters.

(6) It is included a variability in the labor allocated for each task for testing proposal.

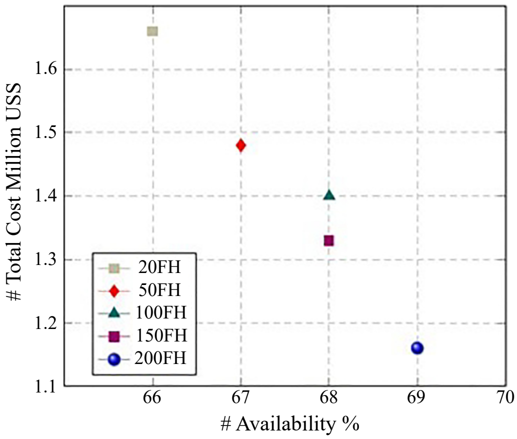
(7) Labor of preventive maintenance based on data of similar task performed on commercial aircraft.

Tests with different steps were conducted to confirm the hypothesis of achieving cost minimization due to task grouping around common resources or preparations.

Figure 4 depicts the results of the experiments with 85 tasks (intervals ranging from 200 FH to 1870 FH), considering a 4500 FH horizon and a standard operational profile (1,500 flight hours per year). It shows that the greater the step interval, the greater is the economy and availability. It is noticed that 200FH is minimum interval of tasks sample.

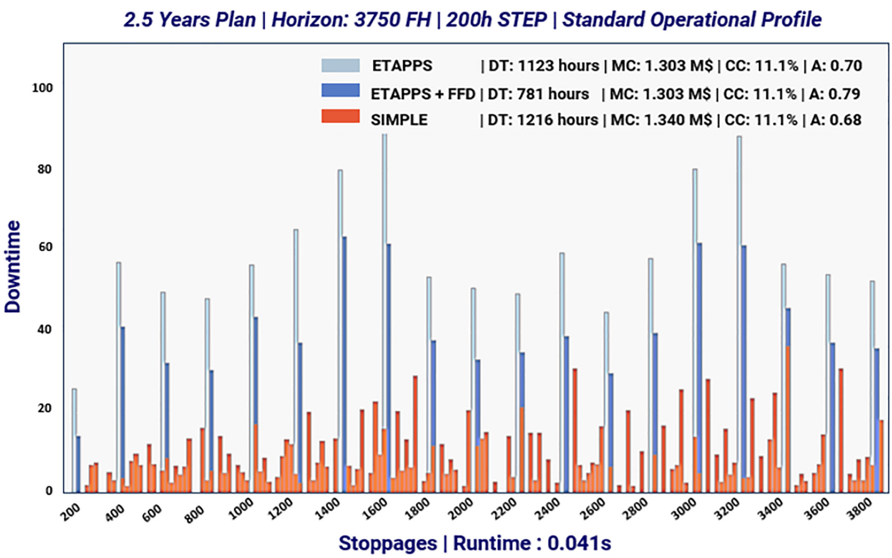
Tests using additional set of tasks were run to confirm and validate the hypotheses of gains in terms of costs and availability and the efficiency of the solver. Figure 5 summarizes the results of 20 experiments considering a 200 FH step interval, standard operational profile (1,500 flight hours per year), using the Simple and the ETTAPS methods.

A decrease in overall expenses amounting to approximately US$37,000.00, or 2.76% over a period of 3,750 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 red bars), that is 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$5,410.00, indicating an improvement in the overall reliability of the aircraft.



Source(s): Authors

Figure 4. Influence of step interval on costs and availability



Source(s): Authors

Figure 5. Comparison of methods with 200-h steps

A noteworthy increase of 11% 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.

Another experiment was performed to validate the Out of Phase factor influence. Table 1 - Experiments results: 85 tasks with out-of-phases hows the results in test using two different factors and 85 tasks.

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 Branch-and-Cut and First Fit

Decreasing algorithms. We ran 20 instances with 85, 170, 255 and 340 tasks each, considering a 200h step, horizon of 5000 FH and a standard profile by using the Simple method with and without FFD, as well as ETAPPS with and without FFD. The values on Figures 6 and 7 are the averages cost and availability of the experiments. It can be observed that with FFD there is an increase in availability because tasks are better packed. ETAPPS showed better results in terms of availability increase and cost reduction in all instances.

7. Conclusion

We developed an innovative model and solution procedure that solves the task allocation and packing problem (TAPP) in the scenario of initial maintenance plan development, where preventive maintenance is a strategic factor for product safety and operational performance.

This study proved that grouping maintenance tasks using an optimization algorithm saves maintenance expenses while improving the availability.

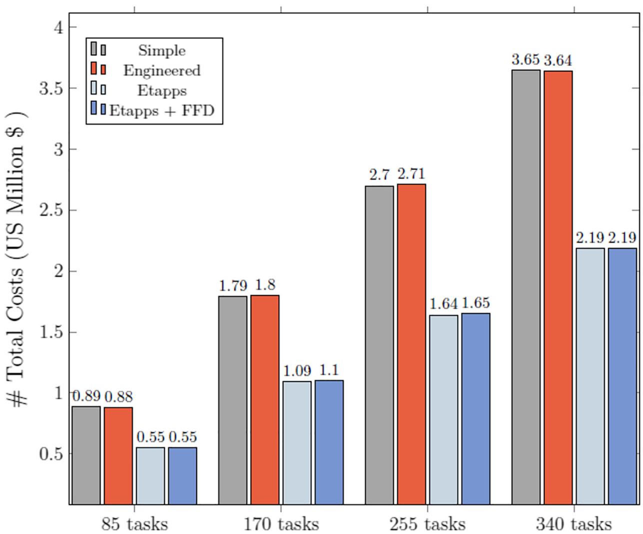
The method provided extended the current maintenance planning studies by investigating how the sequence to perform each task within a package can influence aircraft downtime using the FFD algorithm. For this, the optimization model considered the available resources in each mechanic skill as well as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

It is important to note that the proposed method addresses part of the gaps found in the maintenance plan development process. It satisfies a need in the industry by organizing the

Table 1. Experiments results: 85 tasks with out-of-phase

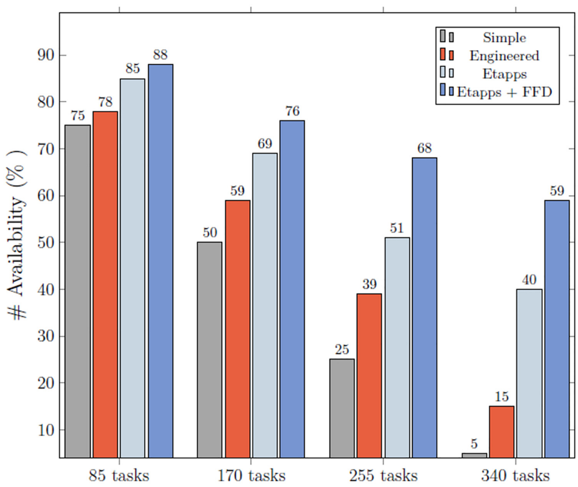
Method	FFD	A	Tot. cost ($)	Corr. cost ($)	Opfactor	Packed	OoP
ETTAPS	YES	0.73	1556309.63	173531.80	1	332	149
	YES	0.80	1425773.44	173436.72	2.8	481	0

Source(s): Authors



Source(s): Authors

Figure 6. Comparison of methods - total costs



Source(s): Authors

Figure 7.
Comparison of methods – availability

tasks resulting from the MSG-3 guidelines and certification analysis to produce an operator maintenance plan.

Our scientific contributions are the definition of a mathematical model and a solution algorithm that integrate two concepts: the maturity and effectiveness of product supportability since the development life cycle phase and looking at the OEM's side task allocating and packing process to elaborate the initial operator 's maintenance plan.

Our practical contributions consist of an in-depth planning process and an algorithm that will foster more confidence in the produced maintenance plan.

In the future, different approaches may be used to investigate the concept of deploying digital twins during product development to evaluate the performance of the resulting maintenance plan in the future operational environment. In addition, more in-depth studies may consider the proactive analysis of field data using the appropriate Artificial Intelligence tools. This could result in the development of a resilient maintenance plan that is modified as situations change. The following topics can also be of interest to the maintenance researcher:

(1) Integration of the model with MSG-3 and maintenance task analysis to during product development, achieving agile and on-time adjustments to the product.

(2) Integrate the model with prognostic health monitoring to assist operators with aircraft maintenance and flight planning decisions.

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