

Article

Planning of Aircraft Fleet Maintenance Teams

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Abstract: This paper addresses a support information system for the planning of aircraft maintenance teams, assisting maintenance managers in delivering an aircraft on time. The developed planning of aircraft maintenance teams is a computer application based on a mathematical programming problem written as a minimization one. The initial decision variables are positive integer variables specifying the allocation of available technicians by skills to maintenance teams. The objective function is a nonlinear function balancing the time spent and costs incurred with aircraft fleet maintenance. The data involve technicians' skills, hours of work to perform maintenance tasks, costs related to facilities, and the aircraft downtime cost. The realism of this planning entails random possibilities associated with maintenance workload data, and the inference by a procedure of Monte Carlo simulation provides a proper set of workloads, instead of going through all the possibilities. The based formalization is a nonlinear integer programming problem, converted into an equivalent pure linear integer programming problem, using a transformation from initial positive integer variables to Boolean ones. A case study addresses the use of this support information system to plan a team for aircraft maintenance of three lines under the uncertainty of workloads, and a discussion of results shows the serviceableness of the proposed support information system.

Keywords: aircraft fleet; linear integer programming; problem of planning; efficiency; maintenance teams; scheduling; optimization



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1. Introduction

The airline industry is nowadays facing a significant crisis caused by the Severe Acute Respiratory Syndrome Coronavirus-2 (SARS-CoV-2), which might in the future be embodied as the most impacting crisis in the history of the industry. According to the latest data in March 2021, the intra-Europe and intercontinental flights are 66% and 58% below 2019 flight levels, respectively, and worldwide flight departures are 40% lower than pre-pandemic levels [1]. This crisis affects all the aviation industry, e.g., aircraft and engine manufacturers, components and materials supply chain, and maintenance and repair organizations (MROs). Some companies will not survive, and many will face mergers and acquisitions. The sector looks for more efficient, cost-effective processes, values flexibility, and searches for new opportunities to endure.

The airline market is highly regulated and monitored, impacting the efficiency of the operation [2]. An airline company that achieves a competitive improvement in aircraft maintenance has gains by giving wings for lower fares, less downtime, higher hangar availability, greater aircraft rotation, and lower operating cost [3]. Therefore, aircraft MRO service is a pivotal action for the airline business in allowing for the reduction of operating costs, improving aircraft punctuality [4] and efficiency [5], while increasing safety and decreasing the likelihood of incidents and accidents [6,7].

Lines of investigation about aircraft MROs aim to reduce aircraft downtime by applying maintenance work scheduling methodologies [8,9], to reduce maintenance costs [10,11], and to create new strategies to improve components and systems reliability [12]. Maintenance activities must comply with specific procedures issued by the manufacturers of aircraft, engines, and components while synchronizing all the resources, such as parts, tools, and technicians. All airlines aim to maximize profit margins, which comprises lowering the operating costs, including aircraft maintenance costs, crew costs, cost of ownership, and fuel costs. Maintenance cost represents about 13% of the airline's total operating cost [13]. In addition, MROs must only release for flight aircraft that meet all safety requirements, i.e., a management system to support decisions of good maintenance practice in due time is required to deliver the aircraft on time.

The line of research pursued by the author is to use the programming language Python, which is an object-oriented programming language that offers software packages with algebraic models to deal with various computational mathematical procedures and commercial solvers for optimization. Concerning computing procedures involved in the research is relevant the Python package Pyomo, which is open-source software with support for libraries and embedded objects to model and solve mathematical formalizations [14]. In addition, relevant is the GLPK—a well-known freeware solver written in ANSI C to solve (mixed-integer) linear programming problems [15] and SciPy—a Python library of numerical routines for modeling and solving scientific problems [16]. This paper has the following structure: Section 2 is about aircraft maintenance, Section 3 presents a configuration of the framework identifying the variable cost and the constraints of the problem, Section 4 presents the formulation of the planning, and Section 5 is about the case study. Finally, Section 6 outlines the conclusions.

2. Aircraft Maintenance

An aircraft MRO is an organization specialized in performing maintenance, repair and overhaul, and actions on an aircraft and components, from the entry into service until the disposal of the aircraft. The aircraft age, a mix of hours flown and landing cycles, regulations issued by aviation authorities, and engineering analysis is data to plan the maintenance package. Daily, the aircraft MRO performs scheduled maintenance tasks, from simple routine ones to complex overhauls to overcome systems and components going into degrading performance. For instance, line maintenance is the scheduled maintenance during the time in transit between flights; A-Check has a duration from 6 to 36 h depending on the fleet, is roughly run every two months, and includes visual inspections, lubrication, and quick components replacements; C-Check, which may be several weeks depending on how heavy the level of disassembly and structural inspection is, runs every 18 to 24 months. Some typical disassembly and structural inspection are the removal of seats, toilets, galleys, overhead compartments, engines, and landing gears.

Airline companies expect that the aircraft fleet is as most fully utilized as possible during the stated useful lifetimes, putting pressure on MROs to mitigate losses of revenue due to downtime and demanding minimal cost and improved reliability. Therefore, an MRO to be competitive must have efficient, efficacious, and effective management. The cost imputed to an aircraft by an MRO is due to the following aspects: direct maintenance cost, including direct labor and materials needed for maintenance tasks, and maintenance burden, including airline overhead, acquisition and maintaining cost of equipment, tools, buildings facilities, and other indirect costs [17]. In addition, meaningful is the opportunity cost due to the number of days for which an aircraft is out of service since inhibited revenue is a virtual disbursement [18]. The direct labor hours of a check is the sum of the duration each group of certified skilled technicians takes to perform the work manageable by the respective skill. In the case study of this paper, direct labor due to teams of certified skilled technicians engaged in performing maintenance tasks have the following skills, i.e., avionics, systems, and structures.

The planning of aircraft maintenance teams is overwhelming for decision-makers to decide without a support information system, i.e., is not compliant with the inherently human expertise. For instance, in Section 5 Case Study, although there are only three aircraft, the number of decisions and constraints involved does not allow an expert to take the most appropriate decision, implying a higher downtime. In addition, in 2018, airlines reported to the International Air Transport Association (IATA) an average direct maintenance cost of \$3.6 million per aircraft and 14% of this value was due to base maintenance [19], meaning a yearly cost of around \$0.5 million in hangar maintenance per aircraft. Additionally, to the direct maintenance cost, the opportunity cost due to downtime affects the total maintenance cost by around 5% daily penalty [20]. Thus, considering the average values, the impact of delaying the hangar downtime by not allocating an optimal team of technicians of the correct skills has a daily impact of \$25,000, showing the relevance of this paper for the airline industry.

3. Framework Setting

The purpose of this paper is to assess the planning of aircraft fleet maintenance teams by defining an appropriate set of certified skilled technicians from a group of available ones [10]. The required data are the values related to the costs breakdown and industrial limitations that influence the allocation of technicians to work in accordance with the required skills for aircraft maintenance. The data are usually obtained, as in other decision contexts, according to the hypothesis that the experience acquired and conveniently updated is the most relevant asset to project future decisions. Thus, the data come from information on past aircraft fleet maintenance checks carried out by an MRO, allowing determining the most convenient number of technicians per skill. Consider from the MRO the data concerning a feasible set $F = \{1, 2, \dots, F\}$ of fleet f to go under a maintenance program. The fleet f is a set $K^f = \{1, 2, \dots, K^f\}$ of aircraft k to go under check c belonging to a set of checks $C_k = \{1, 2, \dots, C_k\}$ that are by contract and regulation mandatory on aircraft k performed by certified skilled technicians X_s in the set of skills $S = \{1, 2, \dots, S\}$, having skill s . In addition, consider that the aircraft fleet f aircraft k under check c has a maintenance cost MC_{kc}^f and revenue opportunity cost RC_{kc}^f , that is, the cost that the company incurs for not flying aircraft k . Then, the sum of all MC_{kc}^f plus RC_{kc}^f is, by assignment, the total cost imputed to maintenance TC on the fleets F , i.e., the expression for cost TC is as follows:

$$TC = \sum_{f=1}^F \sum_{k=1}^{K^f} \sum_{c=1}^{C_k} MC_{kc}^f(t_{kc}^f) + RC_{kc}^f(t_{kc}^f), \quad (1)$$

where t_{kc}^f is the time spent on the respective check, and for fleet f aircraft k to go under check c , and MC_{kc}^f has three main parcels as follows:

$$MC_{kc}^f(t_{kc}^f) = MHC_{kc}^f + MSC_{kc}^f + FAC_{kc}^f(t_{kc}^f), \quad (2)$$

where MHC_{kc}^f is the cost associated with the labor required to perform the maintenance check, that is, the cost due to the hours of work incurred by the use of certified technicians with appropriate skills to perform check c , MSC_{kc}^f is the cost of executing the work package assigned to the aircraft check due to necessary components, materials, and services, that is, the amount disbursed by the MRO in materials, standard parts, chemicals, consumables, components, and expenses with subcontracting services, FAC_{kc}^f is the cost associated with facilities required to perform check c , and cost MHC_{kc}^f is shown as follows:

$$MHC_{kc}^f = h_{kc}^f \sum_{s=1}^S r_{kcs}^f LC_s, \quad (3)$$

where h_{kc}^f is the total labor hours needed to perform the maintenance on fleet f aircraft k under check c ; r_{kcs}^f is the ratio between the maintenance labor hours technicians' skill s on fleet f aircraft k under check c and h_{kc}^f ; and LC_s is the technicians' skill s hourly cost, depending only on a particular skill. Thus, both parameters MHC_{kc}^f and MSC_{kc}^f are, by assumption, fixed costs that do not influence the allocation of technicians, and the decision is independent of the value of these parameters. FAC_{kc}^f is a project-based cost assigned to fleet f aircraft k under check c , depending on the time spent on the respective check t_{kc}^f , and is computed as follows:

$$FAC_{kc}^f(t_{kc}^f) = Fac_{kc}^f t_{kc}^f \quad (4)$$

where FAC_{kc}^f is a project-based cost per hour assigned on fleet f aircraft k under check c and t_{kc}^f is the respective time spent given as follows:

$$t_{kc}^f = \frac{h_{kc}^f}{d} \sum_{s=1}^S \frac{r_{kcs}^f}{x_{kcs}^f}, \quad (5)$$

where x_{kcs}^f are the decision variables determining the number of technicians and r_{kcs}^f are fractions of the total labor hours needed by technicians having the skill s to perform the maintenance on fleet f aircraft k under check c ; d is the daily working period in hours. The cost RC_{kc}^f , incurred by not flying in fleet f aircraft k , is as follows:

$$RC_{kc}^f(t_{kc}^f) = DC_k^f t_{kc}^f \quad (6)$$

where DC_k^f is the daily amount of the lost revenue on fleet f aircraft k . If the time spent on maintenance is less than the scheduled, the aircraft is considered available for flights before the scheduled delivery date. This availability, shortening maintenance time and consequently giving the potential for additional revenue, is an asset that favors the airline. The total number of certified skilled technicians is limited to the available workforce, and the constraint is as follows:

$$\sum_{f=1}^F \sum_{k=1}^{K^f} \sum_{c=1}^{C_k} x_{kcs}^f \leq X_s \text{ for } s = 1, 2, \dots, S, \quad (7)$$

where X_s is the total number of available certified skilled technicians assigned to the feasible set F of fleets f to go under maintenance. In addition, an aircraft under check has a confined working space where the maximum number of technicians can work simultaneously under safety conditions. Therefore, due to the confined spaces available for work, the constraint is as follows:

$$\sum_{s=1}^S x_{kcs}^f \leq A_{kc}^f \text{ for } f = 1, 2, \dots, F; k = 1, 2, \dots, K^f; c = 1, 2, \dots, C_k, \quad (8)$$

where A_{kc}^f is the maximum number of technicians of all skills assigned to work simultaneously on fleet f aircraft k under check c .

4. Problem Formulation

The goal of the support information system for the planning of aircraft maintenance teams is to find, from a set of certified skilled technicians, the team assignment for the maintenance of the set of fleets F . This goal is in the framework of mathematical programming the minimization of the incurred cost of maintenance as shown by Equation (1), subject

to the constraints shown as Equations (7) and (8). An illustration of the setting for the problem is in Figure 1.

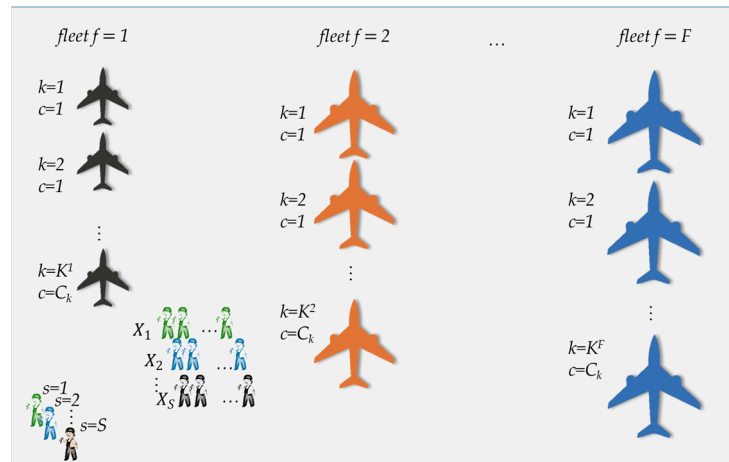


Figure 1. Base maintenance on fleet F with the workforce of set S of certified skilled technicians.

Figure 1 is a setting, for instance, for the base maintenance of the set of fleet F of an aircraft having K^f aircraft for checks from set C_k , by employing the workforce having the partition in certified skilled technicians given in set S .

Only costs that depend directly or indirectly on labor hours incurred by the workforce of certified skilled technicians having appropriate skills to perform the required checks are relevant for the goal of achieving the minimization. Other costs which are not dependent on the decision variables are not meaningful in the scope of the problem formulation. The relevant costs are the variable term of cost MC_{kc}^f shown by Equation (2) and cost RC_{kc}^f shown by Equation (6). The mathematical programming problem is as follows:

$$\min \sum_{f=1}^F \sum_{k=1}^{K^f} \sum_{c=1}^{C_k} (Fac_{kc}^f + DC_{kc}^f) h_{kc}^f \sum_{s=1}^S \frac{r_{kcs}^f}{x_{kcs}^f}, \tag{9}$$

s.t.

$$\sum_{f=1}^F \sum_{k=1}^{K^f} \sum_{c=1}^{C_k} x_{kcs}^f \leq X_s \text{ with } s = 1, 2, \dots, S, \tag{10}$$

$$\sum_{s=1}^S x_{kcs}^f \leq A_{kc}^f \text{ and } x_{kcs}^f \in \mathbb{N} \text{ } f = 1, 2, \dots, F; k = 1, 2, \dots, K^f; c = 1, 2, \dots, C_k, \tag{11}$$

where x_{kcs}^f are the decision variables, giving the number of certified skilled technicians having appropriate skills to perform the checks. The problem is a nonlinear integer programming problem due to the objective function. The time spent with the maintenance of the fleet T^f is a function of x_{kcs}^f given as follows:

$$T^f = \frac{h_{kc}^f}{d} \sum_{s=1}^S \frac{r_{kcs}^f}{x_{kcs}^f}. \tag{12}$$

As is well-known, the objective function of a mathematical programming problem divided by a positive non-null value provides an equivalent objective function to establish the same optimal decisions. For instance, consider a value smw as follows:

$$smw = \min \left\{ (Fac_{kc}^f + DC_{kc}^f) h_{kc}^f; f = 1, 2, \dots, F; k = 1, 2, \dots, K^f; c = 1, 2, \dots, C_k \right\}. \tag{13}$$

Then, let:

$$CR_{kc}^f = (Fac_{kc}^f + DC_{kc}^f)h_{kc}^f / smw; f = 1, 2, \dots, F; k = 1, 2, \dots, K^f; c = 1, 2, \dots, C_k \}, \quad (14)$$

where CR_{kc}^f is the parameter cost ratio for each check c of aircraft k of fleet f relative to the values of the check used as a reference for the maintenance parameter costs. In addition, the problem can be rewritten as a pure integer linear problem to benefit from well-established commercial solvers. The rewritten problem followed in this paper uses the transformation of variables as follows:

$$x_{kcs}^f = \sum_{j=1}^{X_s} j u_{kcsj}^f \text{ with the multiplicative inverse given by } (x_{kcs}^f)^{-1} = \sum_{j=1}^{X_s} u_{kcsj}^f / j, \quad (15)$$

where u_{sj} are the new decision variables, having the Boolean value of 1 if the assignment is performed by technician j ; otherwise, the Boolean value is null. The inverse transformation of Equation (15) is trivial, and every integer decision variable x_{kcs}^f , having values in the set $\{1, 2, \dots, X_s\}$ introduces X_s new Boolean variables u_{sj} , giving a total number of Boolean variables $\#_{Boo}$ as follows:

$$\#_{Boo} = \sum_{s=1}^S X_s, \quad (16)$$

where $\#_{Boo}$ is at least equal to S and may have a much larger number than the total number of the integer variables. After using the transformation of variables given by Equation (15) in Equations (9)–(12), the transformed equation is the formulation for the support information system proposed in this paper stated as follows:

$$\min \sum_{f=1}^F \sum_{k=1}^{K^f} \sum_{c=1}^{C_k} \sum_{s=1}^S CR_{kc}^f \sum_{j=1}^{X_s} \frac{u_{kcsj}^f}{j}, \quad (17)$$

s.t.

$$\sum_{f=1}^F \sum_{k=1}^{K^f} \sum_{c=1}^{C_k} \sum_{j=1}^{X_s} j u_{kcsj}^f \leq X_s \quad s = 1, 2, \dots, S, \quad (18)$$

$$\sum_{s=1}^S \sum_{j=1}^{X_s} j u_{kcsj}^f \leq A_{kc}^f \quad f = 1, 2, \dots, F; k = 1, 2, \dots, K^f; c = 1, 2, \dots, C_k, \quad (19)$$

$$\sum_{j=1}^{X_s} u_{kcsj}^f = 1 \quad s = 1, 2, \dots, S; f = 1, 2, \dots, F; k = 1, 2, \dots, K^f; c = 1, 2, \dots, C_k, \quad (20)$$

$$u_{kcsj}^f \in \{0, 1\}. \quad (21)$$

In Equations (17)–(21), there are no nonlinear terms, i.e., the transformed equation is a pure linear integer programming problem with only Boolean decision variables, benefiting from the efficiency and efficacy of the available commercial optimization solvers, i.e., circumventing the use of nonlinear integer solvers. Other constraints are possible, as long as the transformation of variables shown by Equation (15) does not pass nonlinearities into the transformed formulation. However, for the sake of simplicity, the constraint due to the available workforce shown by Equation (10) and the space for work shown by Equation (11) are the only ones explicitly in the formalization.

5. Case Study

Consider an airline demanding from an MRO three lines of maintenance, one line for large regional aircraft (LRJs), and two lines for small regional aircraft (SRJs). The three lines require the support of a direct labor team of certified skilled technicians in systems,

structures, and avionics. The setting for the problem is two fleets, one with two aircraft and the other with one aircraft, and a partition of the production workforce into three sets of skills, as shown in Figure 2.

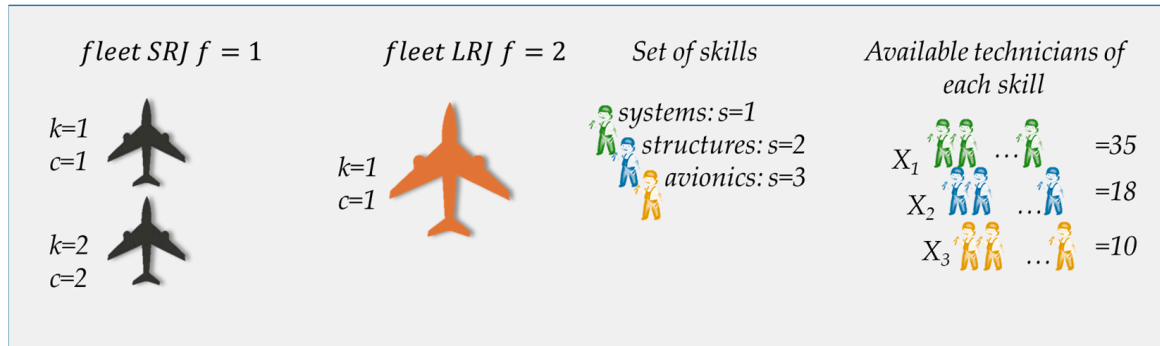


Figure 2. Base maintenance of fleet $F = 2$ and workforce of set $S = 3$ of certified skilled technicians.

Figure 2 is, for instance, the base maintenance of the set of fleets $F = \{1, 2\}$, having fleet sets $K^1 = \{1, 2\}$ and $K^2 = \{1\}$. Fleet $f = 1$ demands for two different checks $C_{k=1} = \{1\}$ and $C_{k=2} = \{2\}$. Some of the data for this planning, especially the one concerned with the costs and the time spent on the check per skilled technicians, have uncertainty, i.e., for the same maintenance, more than one scenario of data occurs in the stored data of the MRO. Eventually, the number of scenarios is high, implying a reduction, for instance, the identification of scenarios showing considerable similarity. However, this identification, given by clustering methodology, deserves an appropriate treatment by an artificial intelligence application, which is out of the scope of this paper. Therefore, the data in the case study are, by assumption, previously treated to deliver the characteristic one for the parameters of the MRO. On average, the ratio of labor hours between SRJ and LRJ checks is 96%, and the partition of labor hours by skills is in Table 1.

Table 1. Average labor by skill relative to each fleet average total labor.

Aircraft	Systems (%)	Structures (%)	Avionics (%)
Small regional aircraft (SRJ)	61%	25%	14%
Large regional aircraft (LRJ)	72%	18%	11%

The average downtime cost ratio due to the revenue loss of SRJs relative to that of LRJs is 50%. The average facilities daily costs relative to the daily downtime cost is in Table 2.

Table 2. Aircraft facilities daily cost relative to each aircraft’s daily downtime cost.

Facilities	LRJ (%)	SRJ (%)
Daily cost	17.5	10

Labor, one factor of production for the check, is scarce in availability and subject to constraints, due to not only the limited skilled technicians under assignment but also the maximum number of technicians due to the confined spaces for SRJ and LRJ checks in compliance with the data shown in Table 3.

Table 3. Number of technicians per skill due to confined spaces.

Technicians	Systems	Structures	Avionics	LRJ	SRJ
Number	35	18	10	40	25

A Monte Carlo simulation implemented in Python generates hundreds of possible maintenance checks, assuming a normal distribution of the population. A random subsample of 99 different scenarios for each of the three aircraft under maintenance stored in a data structure generated 970,299 combinations of maintenance possibilities. The generation of scenarios runs only once to simulate a historic data bank. The problem Equations (17)–(21), modeled in the programming language Python and solved by the solver GLPK Integer Optimizer v4.57 by considering a sample of 970,299 skill workload groupings of systems, structures, and avionics provided by Monte Carlo simulation, assigns the number of technicians needed and the percentage of maintenance checks performed by an optimal team dimension, as shown in Table 4.

Table 4. Technicians needed vs. percentage of checks performed by an optimal team.

#Techn.	SYS	SRJ ₁ STR	AVI	SYS	SRJ ₂ STR	AVI	SYS	LRJ STR	AVI
1	0%	0%	3%	0%	1%	4%	0%	1%	3%
2	0%	1%	27%	0%	5%	29%	0%	2%	13%
3	0%	9%	74%	0%	17%	74%	0%	7%	30%
4	1%	26%	95%	1%	38%	95%	0%	13%	64%
5	4%	49%	99%	4%	61%	99%	0%	22%	91%
6	10%	71%	100%	12%	80%	100%	1%	35%	99%
7	20%	87%	-	25%	92%	-	3%	51%	100%
8	35%	95%	-	42%	97%	-	6%	69%	-
9	50%	98%	-	57%	99%	-	9%	83%	-
10	64%	99%	-	70%	100%	-	13%	93%	-
11	75%	100%	-	80%	-	-	17%	98%	-
12	84%	-	-	88%	-	-	22%	100%	-
13	91%	-	-	93%	-	-	28%	-	-
14	96%	-	-	97%	-	-	34%	-	-
15	99%	-	-	99%	-	-	41%	-	-
16	100%	-	-	100%	-	-	49%	-	-
17	-	-	-	-	-	-	58%	-	-
18	-	-	-	-	-	-	68%	-	-
19	-	-	-	-	-	-	78%	-	-
20	-	-	-	-	-	-	87%	-	-
21	-	-	-	-	-	-	93%	-	-
22	-	-	-	-	-	-	97%	-	-
23	-	-	-	-	-	-	99%	-	-
24	-	-	-	-	-	-	100%	-	-

Table 4 shows the optimal number of technicians required to accomplish the percentage per skill displayed in the workload scenarios selected by the Monte Carlo simulation. This simulation allows feature extraction about the team allocation, ordered triple per skills (systems, structures, and avionics) of technicians that accomplish the maintenance of a percentage of the total amount of the sampled scenarios. For instance, the SRJ₁ needs a team with the triple (9, 6, 3) technicians to complete at least 50% of the sampled population highlighted in orange, a team of technicians with the triple (13, 8, 4) to complete at least 90% of the sampled population highlighted in yellow, and a team of technicians with the triple (16, 11, 6) to complete 100% of the sampled population highlighted in green, but this last allocation is infeasible due to the confined space for this aircraft, i.e., the maximum number of 25 technicians at work is exceeded. The SRJ₂ needs teams of technicians with the triple (9, 5, 3), (13, 7, 4), and (16, 10, 6) to complete at least 50% (orange), 90% (yellow), and precisely 100% (green) of the sampled population, respectively, but the last team allocation is infeasible. The LRJ needs teams of technicians with the triple (17, 7, 4), (21, 10, 5), and (24, 12, 7) to complete at least 50% (orange), 90% (yellow), and precisely 100% (green) of

the sampled population, respectively, but the last allocation is infeasible, i.e., 40 technicians allowed is exceeded. This feature extraction from the scenarios and the other data of the case study allows concluding that, due to the available 63 technicians, only at least 50% of the sampled scenarios are possible to be completed. Therefore, an increase in the number of available technicians is favored, ensuring the completion of a wider percentage above 50% of the sampled scenarios.

The number of different teams, the statistic mode, and the allocation of technicians derived from the data collected from the optimization using the GLPK to address the 970,299 scenarios are in Table 5.

Table 5. Optimal and statistic mode teams provided by the GLPK.

Aircraft	Number of Teams	Team Mode	Team Skills		
			Systems	Structures	Avionics
SRJ ₁	848	19,840	9	5	3
SRJ ₂	854	22,381	8	5	3
LRJ	1682	7897	18	8	4

Table 5 shows that the GLPK provided 848 different teams for the SRJ₁, and the more frequent team appearing 19,840 times has 9 systems, 5 structures, and 3 avionics technicians. For the SRJ₂, the GLPK sets 854 different teams, and the most frequent team has 8 systems, 5 structures, and 3 avionics technicians appearing 22,381 times. For the LRJ, the most frequent team has 18 systems, 8 structures, and 4 avionics technicians. The SRJ₁ and SRJ₂ teams have a similar configuration, i.e., the difference is just only one more system technician. This configuration is, as expected, due to the inputs coming from two random samples of the same distribution. The LRJ has a different team setting, as the sample is from a different distribution and the maintenance for this aircraft allows 60% more mechanics to work simultaneously on the aircraft.

The distribution of the number of technicians into teams for the three aircrafts is in Figure 3.

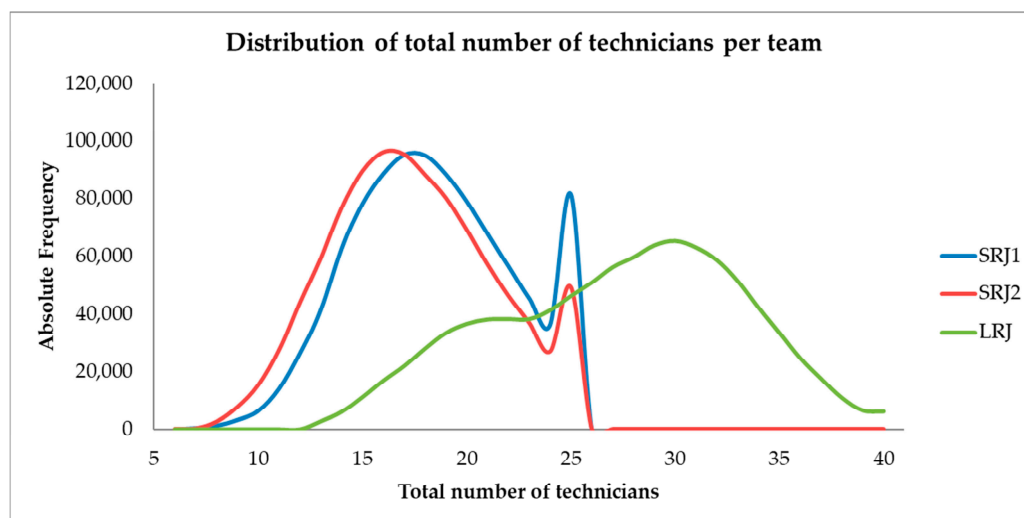


Figure 3. Distribution of the total number of technicians in the teams for the small regional aircraft(SRJ)₁, the SRJ₂, and the large regional aircraft (LRJ).

Figure 3 shows that, until 24 technicians, the distributions for SRJ₁ and SRJ₂ have a similar shape implied by the fact of coming from using the same sample. The SRJ₁ has a mode of 17 technicians, and the SRJ₂ has 16 technicians. The pick at 25 technicians for

SRJ's is due to the constraint of confined spaces becoming active. This allows increasing the allocation of technicians to the LRJ, having a mode of 30 technicians. It would be interesting for the MRO to improve maintenance processes to increase the maximum number of technicians around the SRJ, increasing the support teams, removing some of the work out of the aircraft, and improving the allocation of technicians.

The data regarding the absolute frequencies of teams are in Figure 4.

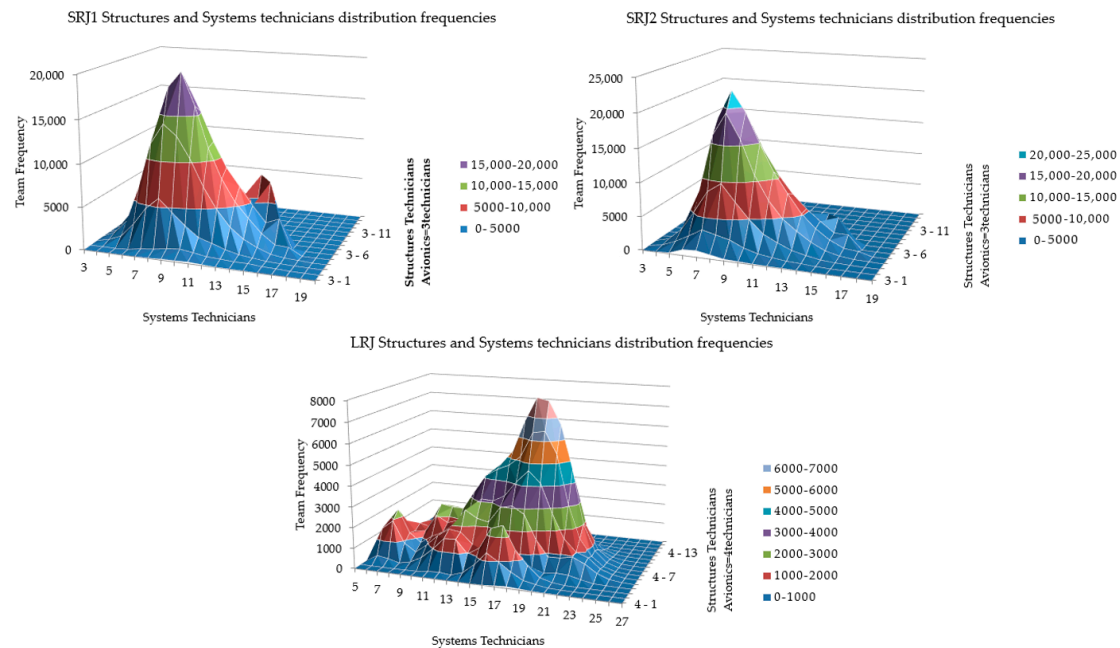


Figure 4. SRJ₁, SRJ₂, and LRJ frequencies of solutions of teams with constant avionics technicians.

Figure 4 shows the absolute frequencies of teams considering for illustration purposes of the scenarios, where the integer solution provides the allocation of a team with 3 avionics technicians for the SRJ₁ and the SRJ₂ and 4 avionics technicians for the LRJ, showing the data associated with 47%, 46%, and 34% of the total amount of scenarios, respectively.

6. Discussion

According to [10], the maintenance cost may increase by more than 10%, when non-optimal solutions are chosen. Figure 4 and Table 5 show the dispersion of optimal solutions for the wide variety of maintenance workloads and the most frequent solutions are only optimal for 1.9%, 2.3%, and 0.8% of the possibilities for the SRJ₁, SRJ₂, and LRJ, respectively. This result indicates the importance of having a software package to support the decision of the allocation of skilled technicians to aircraft maintenance checks. The definition of teams has to be dynamic when a new aircraft enters an MRO for maintenance. The team allocation decision will consider the amount of work that has still not been completed for ongoing maintenance checks and the total amount of work of the entering aircraft. Other aspects such as availability of materials, support equipment, and tools must be taken into account when defining the amount of work available for the team of technicians.

The solvers COBYLA and SLSQP are available in the SciPy optimize package, and the implementation for this case study is straightforward. The methods allow not only a multivariable approach but also the use of restrictions. These two algorithms provide solutions in a continuous space; thus, relaxing the decision variables to continuous ones is possible to obtain a continuous approximation to the integer result. COBYLA and SLSQP provide the exact same solution as the integer solver GLPK for 14.0% and 14.4% of the cases, respectively. Both solvers missed the exact solution around 15% of the cases by 1 technician, around 9% of the cases by 2 technicians, around 4% of the cases by 3 technicians. The COBYLA solver missed the exact solution for 59% of the cases by more than 3 technicians.

SLSPQ missed the exact solution for 58% of the cases by more than 3 technicians. This result shows that the non-integer solvers are not suited for the allocation of technicians to maintenance.

7. Conclusions

The claim that the adequate allocation of technicians to teams for the maintenance of aircraft promotes the mitigation of expenses from airlines is a fact with board consensus in the technical literature. This is due to the possible reduction of costs incurred in the MRO operation of facilities and fleet downtime. The reduction of costs, due to the operation of the facilities and fleet downtime, requires a support information system for aiding the management in the decision of allocation of technicians to teams. Thus, a line of research and development of support for this decision offers a powerful aid to the planning of aircraft fleet maintenance. This paper is a contribution to this planning taken into consideration: the maintenance time required and the partition per skill, the aircraft facilities daily cost and cost arising due to the fleet downtime, the availability of certified technicians per skill, and the confined spaces for the workforce to work in safe conditions. The allocation of technicians to teams is an integer decision problem, and the relaxation of the integer decisions to continuous ones easily solved is, in general, not suitable for this problem due to solutions that are non-integer, severely jeopardizing feasibility. So, the planning developed in this paper is in the framework of an optimization problem written as a non-linear integer programming. This problem, further subject to a transformation of variables from integers to Boolean decision variables, is transformed into a pure linear integer programming problem, allowing the computation by an efficient and efficacious solver well-established for this optimization. A case study shows some of the applications of this planning regarding the extraction of features associated with the cost due to MRO facilities and fleet downtime, the availability of certified technicians per skill, the confined spaces, and scenarios for the workload designed by a Monte Carlo method.

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Nomenclature

Indexes

f	index of fleet
k	index of aircraft
c	index of maintenance check
s	index of skills
j	index and number of technicians assign in a skill

Sets

F	set of fleet
K^f	set of aircraft of fleet f

C_k	set of checks for aircraft k
S	set of all technicians
Parameters	
r_{kcs}^f	ratio of labor hours for fleet f aircraft k check c at work skill s
LC_s	specific cost of the technicians for skill s
WL_{kcs}^f	workload for fleet f aircraft k check c at work skill s
X_s	number of technicians of skill s available to be assigned to the checks
A_{kc}^f	maximum number of technicians allowed to work simultaneously for fleet f aircraft k check c
h_{kc}^f	labor hours for fleet f aircraft k check c
MHC_{kc}^f	cost related to labor for fleet f aircraft k check c
MSC_{kc}^f	cost related to materials, subcontracts, and services for fleet f aircraft k check c
Fac_{kc}^f	cost per day of facilities imputed to fleet f aircraft k check c
DC_k^f	daily revenue loss due to not flying fleet f aircraft k
Objective function	
TC	cost incurred by the airline to perform the checks on the fleets
Dependent variables	
t_{kc}^f	duration in days for the maintenance of fleet f aircraft k during check c
MC_{kc}^f	cost of maintenance-task-related for fleet f aircraft k check c
RC_{kc}^f	the opportunity cost due to not flying fleet f aircraft k during check c
CR_{kc}^f	normalized maintenance cost for fleet f aircraft k check c relative to the reference cost of fleet 1 aircraft 1 check 1, i.e., the value normalized for CR_{11}^1 is 1
FAC_{kc}^f	cost of facilities imputed for fleet f aircraft k during check c
Independent variables	
x_{kcs}^f	number of technicians assigned to fleet f aircraft k check c at work skill s
Binary variables	
u_{sj}	0/1 variables for skill s ; assign of technician j : 1, assign; 0, no assignment

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