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Maintenance Management: A Review on Problems and Solutions

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Abstract

Maintenance management is defined as "all management activities that determine the maintenance requirements, objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and improvement of maintenance activities and economics". The purpose of this research work is to present a brief review on key problems in maintenance management and on selected solutions to address these problems, particularly within aviation maintenance, framed within *business analytics* (BA), which comprises *descriptive*, *predictive*, and *prescriptive* perspectives. Unlike manufacturing, in which most activities are deterministic by nature, characterized by well-defined execution lead times and required resources, being it labor, tools, or parts and materials, maintenance presents an important stochastic component. Maintenance can be divided into *preventive maintenance* and *corrective maintenance*. The former refers to prespecified tasks, carried out at predetermined intervals, being its work essentially deterministic. The latter results from the probabilistic nature of failures, performed upon a fault is identified, being its work inherently stochastic. The workload resulting from corrective maintenance can be more than half of the total maintenance workload according to some studies, making it an important challenge for effective and efficient maintenance management. This research work is expected to be of interest for researchers and practitioners alike, by identifying the sources of uncertainty associated with maintenance management and by providing references on relevant methods to model and control such uncertainty.

Keywords: Maintenance management; Capacity planning; Spare parts management; Scheduling; Business analytics

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1. Introduction

Maintenance is performed in all physical assets to prevent or reduce the occurrence of failures, or to return the assets to an up state, thus increasing their availability, ideally, at a minimum cost [1]. Despite its strategic implications, maintenance is still seen as a "necessary evil" in some economic sectors [2]. To others, maintenance is already treated with due relevance in the development of business strategy [3]. One the one hand, for the owner of the asset, whose core focus is in producing goods or services, maintenance is required to achieve established production levels through asset availability. On the other hand, for the organization providing maintenance, commonly known as Maintenance, Repair, and Overhaul (MRO), its core focus is in improving maintenance performance [4]. Effective and efficient maintenance management is required for both. Maintenance management refers to the activities of establishing maintenance requirements, objectives, strategies and responsibilities, as well as implementing these through planning and control, while improving maintenance activities and economics [5].

In simple terms, maintenance comprises *preventive maintenance* and *corrective maintenance*. The former type of maintenance refers to maintenance actions performed with the purpose of assessing or mitigating degradation and reducing the probability of failure [5]. It is also known as *scheduled maintenance*, or *planned maintenance*, if performed according to a specified time schedule or specified number of units of use, or according to a maintenance plan. The latter refers to maintenance actions performed after fault identification with the purpose of restoring the asset into a state in which it can fulfill its function [5]. It is also known as *unscheduled maintenance*, or *unplanned maintenance*, given it is performed only after a faulty state is detected, which, in turn, depends on the probabilistic nature of failures. While preventive maintenance work is essentially deterministic, characterized by maintenance activities known beforehand and prespecified maintenance resources such as labor, tools, parts and materials, but also budgets, corrective maintenance work is inherently stochastic [6], [7]. The full scope of the corrective maintenance work may only be known at the end of the execution of preventive maintenance. For example, many preventive maintenance activities refer to inspections, such as visual inspections. If in the course of an inspection a faulty state is detected, a corrective maintenance activity, such as a repair, is required to restore the asset. If the repair requires parts or materials with long lead times, or specialized tools or workforce, which may not be readily available, the maintenance process suffers delays, resulting in the extended downtime of the asset [7], [8]. The uncertainty resulting from this lack of information prior to the execution of the maintenance work is one of the most important factors contributing to the complexity of maintenance management.

Maintenance management is about decisions made in the present that will affect actions performed in the future. One the one hand, this decision-making process is limited by the available data at the time of the decision, which is often incomplete, insufficient, or contains variability. This type of uncertainty is called *aleatory uncertainty* [9]. On the other hand, decision-makers must rely on predictions or estimations obtained from inherently imperfect models. This type of uncertainty is called *epistemic uncertainty* [9]. While much of the aleatory uncertainty results from the physical processes of the real world and cannot be reduced or modified, epistemic uncertainty may be reduced and better managed through the use of better prediction models. In maintenance, the aleatory uncertainty refers to the natural degradation of assets over time, observable in the decreasing levels of reliability. Epistemic uncertainty refers to the types of models that are used to predict that natural degradation.

The purpose of this research work is to present a review on key problems affecting maintenance management and on relevant solutions to address these problems, framed within *business analytics* (BA), which comprises *descriptive*, *predictive*, and *prescriptive* perspectives [10].

The review was performed under the following approach: 1) the problems affecting maintenance management have been defined, mainly, based on relevant books including [11], [12], [13], part of the *Springer Series in Reliability Engineering*, and [14], [15]; 2) regarding the selection of solutions to address the identified problems, scientific papers have been retrieved from ScienceDirect, Web of Science, and Google Scholar through the search terms "maintenance capacity planning", "spare parts management", and "maintenance scheduling". The solutions were selected particularly within aviation maintenance, given the importance of maintenance in this sector and the attention it has received from researchers. The selected solutions were then grouped into the three BA perspectives previously enumerated – descriptive, predictive, and prescriptive.

The remainder of the paper is organized as follows. In Section 2, a review on literature addressing concepts and definitions within maintenance management is presented. In Section 3, key problems affecting maintenance management are presented. In Section 4, selected solutions, framed within BA, are reviewed. Finally, in Section 5, conclusions are drawn on the performed work and future research opportunities are identified.

2. Maintenance Management

Maintenance management is formally defined as "all activities of the management that determine the maintenance requirements, objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics" [5]. In particular, the objectives of maintenance management include minimizing idle workforce, maximizing workforce use, materials, and equipment, and, finally, maintaining the equipment operating at a level in which it is capable to fulfill production and quality goals [16]. Being of paramount importance in keeping assets operational at a minimum cost, the subject of maintenance management has been addressed in relevant literature. The book edited by Ben-Daya et al. [14] is a reference in this regard. The book covers a wide range of topics within maintenance management and maintenance engineering, from maintenance organization to maintenance planning and scheduling, from maintenance strategies to maintainability and system effectiveness. In another book Duffuaa and Raouf [15] focus on the planning and control aspects of maintenance management, further elaborating on some of the techniques presented in Ben-Daya et al. [14]. Another important reference in maintenance management is the book of Márquez [11]. The author extends his previous work [17] and proposes a "maintenance management framework", comprising a series of "management blocks", each of which with a clear function within the maintenance management process. For each block, different tools, including models, techniques, and methods used in maintenance engineering, are provided. Other references in maintenance management include the books of Kelly [18], [19], [20]. The author focuses on the strategic, tactical, and operational aspects of maintenance management in each book, respectively.

Maintenance management comprises all three levels of decision: strategic, tactical, and operational [4]. The strategic level deals with the definition of the maintenance strategy, which must be consistent and coherent with other aspects of the business such as production, marketing, finance, etc. The tactical level addresses the planning and scheduling of maintenance activities, considering degradation models for the assets, maintenance policies adopted by the organization operating the assets, and logistics. Finally, the operational level deals with the execution of maintenance activities [4]. Related with the levels of decision, Márquez [21], separates the maintenance management process into two parts: the definition of the maintenance strategy; and the implementation of the strategy. The first part refers to the definition of the maintenance objectives (strategic level), which are derived directly from the business plan, being, for that reason, related to maintenance effectiveness. The second part refers to the ability to ensure the availability of required maintenance resources and to minimize costs (tactical and operational levels), being, therefore, related to maintenance efficiency. In many economic sectors, the definition of the maintenance strategy is limited by the manufacturer of the physical asset (OEM), or by regulatory authorities. This is the case with assets such as aircraft, in which maintenance requirements are pre-established and cannot be changed by aircraft operators. Taking these cases into consideration, the present research work focuses on the problems and solutions affecting the implementation of the maintenance strategy, i.e., it addresses the problems and solutions of the tactical and operational levels of maintenance management.

Three key problems affecting maintenance management include capacity planning, spare parts management, and scheduling. These have been identified as important problems, particularly in aircraft maintenance [7], [22], and are presented in Section 3. In Section 4, techniques used to address these problems are discussed.

3. Maintenance Management Problems

As previously mentioned, this research work focuses on the problems affecting the implementation of the maintenance strategy [21]. Three key problems include capacity planning, spare parts management, and scheduling [7], [22]. Márquez [23] includes maintenance planning and maintenance scheduling as the two first "steps" in the maintenance management process. According to the same author, maintenance planning refers to the identification of required maintenance activities (or tasks), including their scope and frequency, to prepare the maintenance plan. Maintenance scheduling refers to the development of a schedule for the execution of the maintenance activities and the supply of resources. Finally, spare parts management includes the identification and classification of spare parts, the determination of required quantities, and the definition of inventory control policies [24].

Al-Turki [16] compares the complexity of maintenance management, particularly of planning and scheduling, with that of production management. According to the author, three main differences exist, which relate with the sources of uncertainty in maintenance management:

- The demand for maintenance work, i.e., maintenance workload, has more variability than production and the arrival of demand is stochastic.
- Maintenance activities have more variability between them, making standards hard to establish compared to production activities.
- Maintenance planning requires coordination with other functional units in an organization and is a major cause of delays and bottlenecks.

3.1. Capacity Planning

Al-Fares and Duffuaa [6] state that the objective of maintenance capacity planning is to find the balance between available capacity, i.e., workforce, and required capacity, i.e., workload. According to the same authors, available capacity is mostly constant, since it derives from the amount of maintenance workers an organization has. On the contrary, required capacity is mostly fluctuating over time, given its variability, possibly presenting trend or seasonal patterns. This is a crucial strategic function of maintenance management since if the level of available resources is too high, serious inefficiencies may occur, with large amounts of capital wasted on unused resources. If the level of resources is too little, maintenance work may not be effectively performed, potentially reducing the availability of the assets and shortening their lifespan. Taking this discussion into account, Márquez [25] states that the problem of maintenance capacity planning is one of achieving a balance between the downtime cost of the asset and the idle time cost of the maintenance staff.

The process of maintenance capacity planning comprises three steps [6], [25]:

- Estimation of the required capacity, i.e., maintenance workload, for each time period in the planning horizon.
- Determination of the available capacity, i.e., maintenance workforce, for the same time periods.
- Determination of the amount of available capacity to assign to each time period in order to fulfill the required maintenance capacity.

Al-Turki [16] states that any planning activity should start by forecasting the future. This is in accordance with the previous steps. In fact, accurate forecasting is of the utmost importance for an adequate estimation of required maintenance capacity. Although not being trivial activities, the determination of available capacity and of the amount of available capacity to assign to each time period are, arguably, easier to address than the estimation of required capacity through forecasting. This is because if an accurate and timely estimation of future maintenance workload exists, even if the available capacity exceeds or falls short of the required capacity, contingency actions may be adopted such as allocating regular in-house crews to other tasks or resorting to overtime and contract maintenance, respectively [26].

3.2. Spare Parts Management

The main purpose of spare parts inventories is to avoid long maintenance downtime, which can be severely affected by supply lead times of replacement parts that are not readily available [24]. Nonetheless, spare parts inventories may significantly increase costs, not being practical to stock all parts and components prone to failure. The use of spare parts may be specific, their demand may be highly random, and their lead time may be highly variable or unknown. In addition, while in stock, spare parts may be prone to obsolescence or degradation and are hardly resalable [24].

There are three key aspects to consider in spare parts management [24]:

- Identification and classification of spare parts.

- Determination of required quantities.
- Definition of inventory control policies.

The first aspect refers to the selection of parts and components that should be stocked. Technical, economic, and operational criteria should be considered in the selection process, with parts ranked through Pareto analysis or multicriteria methods. The second aspect refers to the estimation of quantities of the spare parts previously selected to acquire. If no failure data exists regarding the spare parts, quantities may be based on OEM recommendations, or on records from similar equipment. Otherwise, reliability-based, or forecasting-based procedures can be employed [24]. Reliability-based procedures resort to reliability functions to estimate time-to-failure and number of replacements at failure. Forecasting-based procedures resort to past observations to estimate future levels of activity, in this case the required number of spare parts [27]. Typically consider parameters include spare parts demand interval variability and demand size variability [28]. Finally, the third aspect refers to the inventory analysis, including the definition of the frequency to assess the inventory status, the definition of order instants for parts restocking, and the definition of order quantities [24].

3.3. Scheduling

According to Al-Turki [16], maintenance scheduling is the process of matching maintenance activities with resources, in which the activities are sequenced to be executed at certain points in time according to their interrelations, the availability of resources, and other limitations and constraints. The efficiency of maintenance scheduling can be assessed through different measures such as meeting due dates, time of completion, or utilization of resources. Márquez [29] presents a similar definition of maintenance scheduling to that of Al-Turki [16]. In addition, the author lists a set of aspects that are required to be considered when producing a maintenance schedule:

- Precise work orders, with clear instructions regarding the work to be performed, required resources, and procedures.
- Time standards for each maintenance activity, based on time measurements.
- Information regarding available resources, including technicians, spare parts inventory status and procurement information, tools and other specific maintenance equipment.
- Production schedule information, including time periods available for maintenance.
- Maintenance activities priorities, established together with the production department.
- Information about scheduled maintenance activities, ongoing and delayed.

When compared to production activities, Al-Turki [16] identifies the following challenges when scheduling maintenance activities:

- Maintenance activities are highly uncertain regarding duration and resource requirements.
- Maintenance activities are highly related regarding precedence relations and relative priority.
- Maintenance activities can be divided into sub-activities, each with different requirements.
- Maintenance activities can be interrupted or canceled due to changes in the operational context.

4. Maintenance Management Solutions

Given the importance and complexity of the aforementioned problems to the maintenance management process, multiple solutions have been proposed over time to address them. A review of some of these solutions is presented in this Section, framed within BA and applied particularly in aviation maintenance. The expression “business analytics” is widely used in various contexts, but no commonly accepted definition exists for what it is [30]. BA can be defined as the use of data through statistical analysis, quantitative methods, and mathematical models to improve decision-making in organizations [10]. This research work adopts the taxonomy related to *what analytics does* [31], under which BA is divided into *descriptive analytics*, *predictive analytics*, and *prescriptive analytics* [10], [32]. Specifically in maintenance, Karim et al. [33] propose a concept for knowledge discovery with focus on big data and analytics called *maintenance analytics* (MA).

4.1. Descriptive Analytics

Descriptive analytics refer to the use of data to gain insights about past and present business performance to allow informed decisions [10]. This is the most common type of analytics, in which data is summarized in charts and reports. Techniques within this type of analytics include descriptive statistical measures, probability distributions, sampling, and statistical inference.

Regarding the application of descriptive analytics techniques to maintenance management, Dinis et al. [7] propose a framework for the qualitative and quantitative characterization of maintenance work to support MRO organizations. The framework, developed in an aircraft maintenance context, comprises a 3-dimensional coordinate system including aircraft zones, project phases, and technical skills, under which maintenance work is statistically characterized. The authors claim that the proposed framework can be used for capacity planning, spare parts management, and maintenance scheduling.

4.2. Predictive Analytics

Predictive analytics refer to the use of historical data to make predictions, exploiting patterns and relationships in the data, and extrapolating them into the future [10]. Techniques within this type of analytics include regression analysis, forecasting techniques, data mining, simulation, and risk analysis.

Including Bayesian networks (BN) in predictive analytics techniques, several studies apply this technique in maintenance management. In capacity planning, Kellenbrink et al. [34], Steffen C. Eickemeyer et al. [35], and Dinis et al. [36] use BN to estimate the workload in aircraft maintenance. In other works, BN are combined with exponential smoothing models to predict the workload of future and unprecedented aircraft maintenance interventions [37], [38].

In spare parts management, several studies employ forecasting techniques in maintenance contexts. Examples include [39], [40], [41], [42], [43]. Ghobbar and Friend [44] compare the accuracy of 13 forecasting methods in forecasting spare parts in aircraft maintenance. Bacchetti and Saccani [45] present a review on forecasting methods addressing spare parts classification and demand forecasting for stock control.

Regarding scheduling, only the work of Öhlinger et al. [46] has been found employing an artificial intelligence-based approach for forecasting maintenance orders for MRO scheduling.

4.3. Prescriptive Analytics

Finally, prescriptive analytics refer to the use of data to find the best alternative from a set of alternatives, which, given its size, involve too many choices for a human decision-maker to effectively consider [10]. Techniques within this type of analytics include linear and non-linear optimization, integer optimization, heuristics, and decision analysis.

In capacity planning, Dijkstra et al. [47] proposes a decision support system (DSS) to support maintenance management in determining the required size and composition of the workforce in a major aircraft MRO. The authors resort to integer optimization to address the problem. Other authors using optimization approaches in maintenance capacity planning include [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], to provide some examples.

In spare parts management, Gu et al. [58] present two non-linear programming models to find the optimal order time and order quantity of aircraft spare parts. Wang [59] propose a stochastic dynamic programming model for joint spare parts inventory and planned maintenance optimization. Zanjani and Nourelfath [60] develop an integrated mathematical programming model for spare parts logistics and operations planning in maintenance. Erkoc and Ertogral [61] develop an integer programming model to optimize overhaul start times for rotable spare parts. Hu et al. [62] present a review of studies using operations research (OR) in spare parts management. Van Horenbeek et al. [63] present a review on joint maintenance and inventory optimization models. Lolli et al. [64] use machine learning for multi-criteria inventory classification applied to intermittent demand.

In scheduling, [65], [66], [67], [68], [69], [70] employ optimization approaches to solve scheduling problems in maintenance, particularly in aircraft maintenance.

5. Conclusions and Future Research

The purpose of this research work is to present a brief review on key problems affecting maintenance management and on selected solutions addressing each of these problems, framed within BA and applied, particularly, in aviation maintenance. Three key problems in maintenance management include capacity planning, spare parts management, and maintenance scheduling. The first problem refers to the estimation of maintenance workload, the determination of maintenance capacity, and the combination of both. The second problem refers to the identification of spare parts, the determination of required quantities, and the definition of inventory control policies. Finally, the third problem refers to the definition of a time frame for the maintenance activities to be performed, while matching their execution with the required resources.

Regarding reviewed solutions, these have been framed according to a three-fold taxonomy of BA, in which BA is divided into descriptive analytics, predictive analytics, and prescriptive analytics. Descriptive analytics refers to the use of past or present data to gain insights about the business to improve decision-making. Predictive analytics refers to the use of historical data to predict the future by exploiting patterns and relationships in the data. Finally, prescriptive analytics refers to the use of data to select an alternative from a set of alternatives which, given its dimension, would be impossible for a human decision-maker to effectively consider.

From the performed review, although brief and focused on aviation maintenance, one can observe that the number of studies addressing each of the possible problem/solution combinations, from the aforementioned problems and solutions, is uneven. Regarding studies employing descriptive analytics techniques, only one study has been found. Only one study has been found as well addressing the scheduling problem from a predictive analytics perspective. On the contrary, multiple studies have been found addressing spare parts management from a predictive analytics perspective, as well as addressing any of the three problems from a prescriptive analytics perspective.

As for future research, a more exhaustive review should be performed considering the presented maintenance management problems and the adopted taxonomy of BA. From the performed review, some indications exist regarding the affinity of some of the BA perspectives with some of the problems. This may result from a more mature scientific field, such as is the case with OR, and would explain the number of studies found within the prescriptive perspective addressing all of the problems affecting maintenance management. In addition, the emergence of monitoring sensors in complex systems, and the connection of these sensors to information networks, i.e., Internet of Things, allows the collection of enormous amounts of data. The exploitation of this data for maintenance management, through techniques such as Machine Learning, which will expectedly contribute to the predictive and prescriptive perspectives of BA, presents another research opportunity.

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