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Beyond its cost, the *value* of maintenance: An analytical framework for capturing its net present value ☆

Karen B. Marais [a,*], Joseph H. Saleh [b]

[a] School of Aeronautics and Astronautics, Purdue University, USA
[b] School of Aerospace Engineering, Georgia Institute of Technology, USA

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ABSTRACT

Maintenance planning and activities have grown dramatically in importance across many industries and are increasingly recognized as drivers of competitiveness if managed appropriately. Correlated with this observation is the proliferation of maintenance optimization techniques in the technical literature. But while all these models deal with the cost of maintenance (as an objective function or a constraint), only a handful addresses the notion of value of maintenance, and seldom in an analytical or quantitative way.

In this paper, we propose that maintenance has intrinsic value and argue that existing cost-centric models ignore an important dimension of maintenance, namely its value, and in so doing, they can lead to sub-optimal maintenance strategies. We develop a framework for capturing and quantifying the value of maintenance activities. Our framework is based on four key components. First, we consider systems that deteriorate stochastically and exhibit multi-state failures, and model their state evolution using Markov chains and directed graphs. Second, we consider that the system provides a flow of service per unit time. This flow in turn is "priced" and a discounted cash flow is calculated resulting in a present value (PV) for each branch of the graph—or "value trajectory" of the system. Third as the system ages or deteriorates, it migrates towards lower PV branches of the graph, or lower value trajectories. Fourth, we conceptualize maintenance as an operator (in a mathematical sense) that raises the system to a higher PV branch in the graph. We refer to the value of maintenance as the incremental PV between the pre- and post-maintenance branches of the graphs minus the cost of maintenance. The framework presented here offers rich possibilities for future work in benchmarking existing maintenance strategies based on their value implications, and in deriving new maintenance strategies that are "value-optimized."

1. Introduction

Maintenance planning and activities have grown dramatically in importance across many industries. This importance is manifested by both the significant material resources allocated to maintenance departments as well as by the substantial number of personnel involved in maintenance activities in companies—for example over a quarter of the total workforce in the process industry is said to deal with maintenance work [1]. This situation, coupled with an increasingly competitive environment, creates economic pressures and a heightened need to ensure that these considerable maintenance resources are allocated and used appropriately, as they can be significant drivers of competitiveness—or lack thereof if mismanaged.

In response to these pressures, the notion of "optimality" and the mathematical tools of optimization and operations research (OR) have seeped into maintenance planning, and resulted in the proliferation of "optimal" maintenance models (see the reviews by Pham and Wang [2] and Wang [3], for example). In each "optimal" maintenance model developed, an objective function is first posited, then analytical tools are used to derive a maintenance policy that maximizes or minimizes this objective function subject to some constraints. For example, the objective function can be the minimization of cost (cost rate, or life cycle cost) of maintenance given a system reliability and/or availability constraint; conversely, the objective function can be the maximization of reliability or availability, given a cost constraint. In addition to varying the objective function, different "optimal" maintenance models are obtained by: (1) varying for example the system configuration (e.g., single-unit systems versus multi-unit systems, *k*-out-of-*n* systems); (2) by including several degrees of maintenance (e.g., minimal, imperfect, perfect); (3) by varying the planning horizon; (4) by using different analytical tools; or (5) by

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* Corresponding author. Tel.: +1 765 494 5117; fax: +1 765 494 0307.
E-mail address: karen.marais@alum.mit.edu (K.B. Marais).

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positing different types of dependencies between the various units in a multi-unit system.

Yet, while all these models deal with the cost of maintenance (as an objective function or a constraint), only a handful of models touches on the notion of *value* of maintenance, and seldom in an analytical or quantitative way (e.g., [24]). Wang [3] highlights a critical idea for the development of a value-based perspective on maintenance when he suggests that the cost of maintenance as well as the resulting system reliability should be considered together when developing optimal maintenance strategies. Unfortunately, where the benefits of maintenance are considered, it is usually in the sense of avoiding the costs of failure. Interestingly, it is only within the civil engineering community that the benefits in the sense of service delivery are considered and cost-benefit considerations explicitly taken into account in the development of maintenance strategies (e.g., [24]).

The argument for dismissing or not focusing on the value of maintenance, when it is made, goes along these lines: while it is easy to quantify the (direct) cost of maintenance, it is difficult to quantify its benefits. Other authors wishing to consider the value of maintenance lament the difficulties in quantifying the benefits of maintenance. Dekker [4] for example notes "the main question faced by maintenance management, whether maintenance output is produced effectively, in terms of contribution to company profits, [...] is very difficult to answer". Therefore maintenance planning is usually shifted from a value maximization problem formulation to a cost minimization problem (see [5,6] for a discussion of why these two problems are not the same and do not lead to similar decisions in system design and operation). Incidentally, in many organizations, maintenance is seen as a cost function, and maintenance departments are considered cost centers whose resources are to be "optimized" or minimized. In short, as noted by Rosqvist et al. [7] cost-centric mindset prevails in the maintenance literature for which "maintenance has no intrinsic value".

In this paper, we argue that maintenance has intrinsic value and argue that existing cost-centric optimizations ignore an important dimension of maintenance, namely its value, and in so doing, they can lead to sub-optimal maintenance strategies. We therefore develop a framework for capturing and quantifying one important aspect of the value of maintenance activities, their impact on revenue-generation capability, by connecting an engineering and OR concept, system state, with a financial and managerial concept, the net present value (NPV).[1] Here the system state refers to the condition of the system and hence its ability to perform and thereby provide a flow of service (hence generate revenue, or "quasi-rent"). In order to build this connection, we first explore the impact of a system's state on the flow of service the system can provide over time—for a commercial system, this translates into the system's revenue-generating capability. Next we consider the impact of maintenance on system state evolution and hence value generation capability over time. We then use traditional discounted cash flow techniques to capture the impact of system state evolution with and without maintenance on its financial worth, or NPV. For simplification, we call the results of our calculations the 'value of maintenance'. Finally, we discuss the advantages and limitations of our framework. This work offers rich possibilities for assessing and benchmarking the value implications of existing maintenance policies, and deriving new policies based on maximizing value, instead of minimizing cost of maintenance.

[1] Note that we consider "value" as the net revenue generated by the system over a given planning horizon. We do not consider additional dimensions of value such as the potential positive effects of maintenance on environmental or health impacts. Such effects can be incorporated in future work, see, for example, Marais et al. [25] for a discussion of the quantification of environmental and health impacts of aviation.

2. Background

This section provides a brief overview of various maintenance models. The purpose of this section is to provide context and background to the model assumptions and analytics we develop in Sections 3 and 4. The reader interested in extensive reviews of the subject is referred to the survey papers by Dekker [4], Pham and Wang [2] and Wang [3]. In the following, we discuss (1) maintenance classification, (2) maintenance models, and (3) maintenance policies.

2.1. Types and degrees of maintenance

Maintenance refers to the set of all technical and administrative actions intended to maintain a system in or restore it to a state in which it can perform at least part of its intended function(s) [4]. Fig. 1 provides a simple (not comprehensive) classification scheme of maintenance along three axes: (1) the type of maintenance; (2) the degree of maintenance; and (3) type of system to be maintained (system configuration can be conceived of as a subset of this axis).

Maintenance type can be classified into two main categories: corrective maintenance and preventive maintenance (PM) [2]. CM, also referred to as repair or run-to-failure (RTF), refers to maintenance activities performed after a system has failed in order to restore its functionality.

PM refers to planned maintenance activities performed while the system is still operational. Its aim is to retain the system in some desired operational condition by preventing (or delaying) failures. PM is further sub-divided into clock-based, age-based, and condition-based. These sub-divisions refer to what triggers maintenance activities [8].

- Clock-based maintenance is scheduled at specific calendar times; its periodicity is preset irrespective of the system's condition (e.g., every Tuesday).
- Age-based maintenance is performed at operating time intervals or operating cycles of the system (e.g., every 500 on/off cycles, or every 4000 h of flight).
- Condition-based maintenance is triggered when the measurement of a condition or state of the system reaches a threshold that reflects some degradation and loss of performance of a system (but not yet a failure). Condition-based maintenance is also referred to as predictive maintenance.

Opportunistic maintenance encompasses both corrective and PM and is relevant for multi-unit systems with economic and functional dependencies in which the failure of one unit, and hence its corrective maintenance, offers an opportunity to perform PM on other still functional units.

Each type of maintenance can be further classified according to the degree to which it restores the system [2]. At one end of the spectrum, perfect maintenance restores the system to its initial operating condition or renders it "as good as new". At the other end of the spectrum, minimal repair returns the system to the condition it was in immediately prior to failing (in the case of corrective maintenance), or "as bad as old". In between these extremes lies imperfect maintenance, which in effect returns the system to a condition somewhere in between as good as new and as bad as old. Finally, there is also the possibility that maintenance leaves the system in a worse condition than before the failure,