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Making Optimal and Justifiable Asset Maintenance Decisions

Andrei Furda[1]; Michael E. Cholette; Lin Ma; Colin Fidge; Wayne Hill; Warwick Robinson

Abstract Maintenance decisions for large-scale asset systems are often beyond an asset manager's capacity to handle. The presence of a number of possibly conflicting decision criteria, the large number of possible maintenance policies, and the reality of budget constraints often produce complex problems, where the underlying trade-offs are not apparent to the asset manager. This paper presents the decision support tool "JOB" (Justification and Optimisation of Budgets), which has been designed to help asset managers of large systems assess, select, interpret and optimise the effects of their maintenance policies in the presence of limited budgets. This decision support capability is realized through an efficient, scalable backtracking-based algorithm for the optimisation of maintenance policies, while enabling the user to view a number of solutions near this optimum and explore trade-offs with other decision criteria. To assist the asset manager in selecting between various policies, JOB also provides the capability of Multiple Criteria Decision Making. In this paper, the JOB tool is presented and its applicability for the maintenance of a complex power plant system.

1.1 Introduction

Maintenance decisions for large-scale asset systems are often beyond an asset manager's capacity to handle. The presence of a number of possibly conflicting decision criteria, the large number of possible maintenance policies, and the reality of budget constraints often produce complex problems, where the underlying trade-offs are not apparent to the asset manager. For example, while one of the major objectives is to reduce costs by avoiding unnecessary maintenance work, another, conflicting objective is to improve the system availability and reliability.

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[1] A. Furda (✉), M. E. Cholette, L. Ma, C. Fidge
Science and Engineering Faculty
Queensland University of Technology, Brisbane, Australia
e-mail: {andrei.furda}|{michael.cholette}|{l.ma}|{c.fidge}@qut.edu.au

W. Hill, W. Robinson
Delta Electricity, Wallerawang NSW 2845, Australia
e-mail: {wayne.hill}|{warwick.robinson}@de.com.au

Furthermore, in addition to clearly defined optimisation criteria, asset managers often rely on their experience, knowledge, and other external system-specific factors, which are very difficult to model in a purely optimisation-based tool. In contrast to optimisation tools, decision support tools provide not only optimisation results, but also allow asset managers to interactively select and analyse various alternatives, and also compare them to suggested optimal choices.

This paper presents the decision support tool JOB (Justification and Optimisation of Budgets), which has been developed by CIEAM (Cooperative Research Centre for Infrastructure and Engineering Asset Management) and QUT (Queensland University of Technology). The JOB tool has been designed to help asset managers of large systems assess, select, interpret and optimise the effects of their maintenance policies in the presence of limited budgets. This decision support capability is realized through an efficient, scalable backtracking-based algorithm for the optimisation of maintenance policies, while enabling the user to view a number of solutions near this optimum and explore trade-offs with other decision criteria.

The remainder of this paper is structured as follows. Section 0 gives an overview of related research, section 0 presents the basic theory of the JOB tool, section 0 elaborates on the application of JOB in a power plant case study. Section 0 concludes this paper.

1.2 Related Work

System maintenance has evolved from a necessary productivity maintaining activity into an important business and asset management activity, resulting in significant research efforts dedicated to system maintenance. An overview study of the maintenance of complex systems can be found in [1] and [2], the topic of asset maintenance management is addressed in details in [3] and [4]. A maintenance decision support system overview is presented in [5], a specific solution suggestion using the Analytical Hierarchy Process (AHP) and Fuzzy Logic is presented in [6], [7] suggests a multi-agent based approach. None of these publications have presented an effective system framework that is tested in a real business environment.

The approaches applied in the JOB decision support tool are well-founded and often applied in combinatorial optimisation and decision making. However, to the best of the authors' knowledge, their application for maintenance decision support, especially for Power Plant systems, is absent from published literature. Furthermore, one of the main aspects which make the JOB tool stand out is its advanced state of applicability in industry as a commercialization ready outcome of the research and utilisation. The JOB tool has been developed in cooperation with one of the largest electricity generators in Australia, specifically for maintenance decisions of power plant systems. Nevertheless, due to the advanced software architecture, its application is not limited to such systems, but can be extended to other complex systems of asset intensive industry.

2.1 Theory and Solution Methods of JOB

The presence of a number of possibly conflicting decision criteria, the large number of possible maintenance policies, and the reality of budget constraints often produce complex problems, where the underlying trade-offs are not apparent to the asset manager. JOB's purpose is to assist decision maker to select a maintenance option for each component of the complex system under a constrained budget, while optimising globally a number of (possibly competing) decision criteria. For example, the goal can be to reduce failure rates and the decision risk, while at the same time minimizing the system downtime due to maintenance and remaining within a specified budget.

Figure 1: JOB data input user interface.

The decision support functionality provided by the JOB tool relies on the solution of a number of (combinatorial) optimisation problems, where the maintenance options are the decision variables and the objective is to minimize various decision criteria that have business relevance, e.g. return on investment, failures per year, etc.

Each system component $i, i = 1,2, .., n$ has maintenance options $o_j^i, j = 1,2, \dots, m_i$ which indicate the type of maintenance, costs, needed time, etc. For example, a component could be replaced entirely, or only partially replaced, and repaired partially (Figure 1). Figure 2 shows JOB’s analysis tab with a typical solution space.

A maintenance policy,A, is defined by a selection of options for each system component $A = (a_1, a_2, \dots, a_i, \dots, a_n)$, where:

$$a_i \in \{o_1^i, o_2^i, \dots, o_{m_i}^i\} \triangleq D_i$$

The set of all possible solutions is $\mathcal{A} = D_1 \times D_2 \times \dots \times D_n$ and thus $\mathrm{A} \in \mathcal{A}$ is the set of all possible policies in the absence of additional constraints.

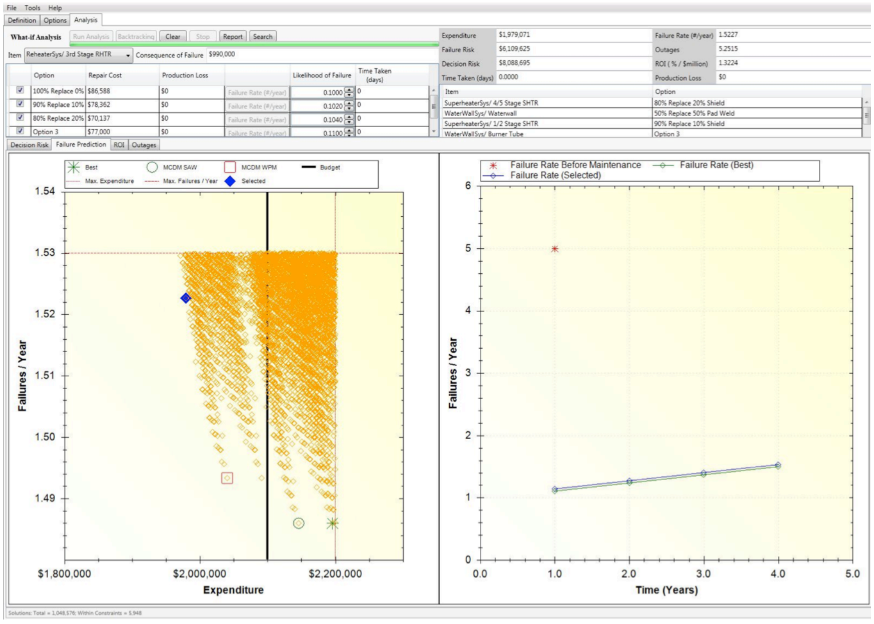

Figure 2: JOB analysis and results user interface.

The set of *feasible* maintenance policies is denoted as

$$\mathcal{C} \triangleq \mathcal{A} \cap \mathcal{C}_{constraint}$$

$$\mathcal{C}_{constraint} = \{\mathrm{A} \mid B_\ell \leq cost(A) \leq B_u \text{ and } LB_{DC_{limit}} \leq v_{DC_{limit}}(\mathrm{A}) \leq B_{DC_{limit}}\}$$

which is the set of all maintenance policies that satisfy *all* constraints. This can now be stated in the compact form

$$\min_{A} J_{obj}(\mathrm{A})$$

$$\text{subject to:} \qquad \mathrm{A} \in \mathcal{C} \qquad \text{(OP)}$$

Since each maintenance option of each system component can be combined with each maintenance option of a different component, this leads to a combinatorial problem with exponential complexity. The following sections address solution approaches.

2.1.1 Solution via Exhaustive Enumeration

The simplest way to solve this optimisation problem is a complete enumeration of all maintenance policies by generating all possible combinations of maintenance options and calculating the decision criteria values for each solution. This is also desirable for decision support, since one can examine any policy and its effect on any criterion. The number of policies in the solution space A is

$$|A| = \prod_{n=1}^{N} opt_n$$

where N denotes the number of system components and opt_n denotes the number of maintenance options for component n. Due to this combinatorial complexity, the complete enumeration of all solutions is feasible only for a system with a low number of constituent components, each with only a few options. Larger solution spaces will exceed the memory limitations if complete enumeration is pursued. The following section presents a solution to this problem.

2.2.2 Solution via Backtracking Based Algorithm

To remedy the problems related to memory and runtime limitations for systems composed with medium-to-large numbers of components, JOB utilizes a search strategy called *backtracking* [8] which explores the feasibility of partially-specified solutions prior to completing them.

When a partially-specified maintenance policy, $\widehat{\mathrm{A}} = (a_1, a_2, \ldots, a_k, \times, \ldots, \times)$ does not satisfy the problem constraints, the algorithm backtracks by unassigning a_k, since it was this assignment that resulted in the constraint violation. This back-tracking discards entire sets of infeasible maintenance policies *en masse*, saving computational effort. If previously unexplored selections of $a_k$exist, the algorithm assigns one of these and the process is repeated. The algorithm terminates when the backtracking operation results in a completely unassigned maintenance policy and there are no unexplored maintenance options for the first component.

2.2.3 Multiple Criteria Optimisation

Multiple Criteria Decision Making (MCDM) is a widely applied discipline used to support decision makers deal with multiple and often conflicting objectives. MCDM problems are subdivided into two categories:

- Multiple Attribute Decision Making (MADM) techniques address discrete problems (i.e. the set of decision alternatives is discrete)[9], [10], while
- Multiple Objective Decision Making (MODM) techniques address continuous decision making problems [11].

The JOB tool supports discrete decision alternatives, and currently implements two of the most widely used decision making techniques:

- Simple Additive Method, and
- Weighted Product Method [10].

The subset of feasible maintenance policies (i.e. decision alternatives) is calculated by applying constraints on the set of alternatives provided by either exhaustive search, or the backtracking algorithm. Maintenance policies with decision criteria values outside the constraint limits are excluded from the set of feasible alternatives.

Each feasible maintenance policy is evaluated with respect to each decision criterion as follows. In a first step, the maximum and minimum are calculated and stored for each decision criterion.

Decision criteria are either of cost or of benefit type. Cost-type criteria are "better" for lower values, while benefit-type criteria are "better" for higher values. The goal is to minimize cost type criteria, and maximize benefit type criteria. This is taken into account when calculating the value function for each alternative and each decision criterion. Cost type criteria are expenditure, Decision Risk, failures, outages, while the return on investment (ROI) is a benefit criterion.

3.1 Application: Maintenance Decision Support for a Power Plant

The JOB decision support tool has been developed in close cooperation with a large power generation enterprise in Australia, with the purpose of applying it in real decision scenarios for optimising the major maintenance of power plant systems.

A planned major power plant maintenance shut-down will be used to evaluate the results provided by the JOB tool against the decision made by an expert human decision maker.

One of the test data sets for the evaluation is based on shut-down maintenance information of partial components of a large boiler system, which requires the analysis of approximately 33.5 million possible maintenance policies.

4.1 Conclusion

This paper has presented JOB, an innovative maintenance decision support tool, which has been specifically developed to support asset managers with the challenge of large-scale maintenance decisions. Besides an exhaustive enumeration algorithm, the JOB tool solves the combinatorial optimisation problem using a highly scalable backtracking based algorithm, which allows the analysis of large systems in an efficient way. Furthermore, the JOB tool is able to suggest optimal maintenance policies based on Multiple Criteria Decision making techniques. A real-world case study attests its capability to support decision makers with complex maintenance decisions and its potential to save costs while even improving the system availability.

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