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Bi-criteria risk analysis of domain-specific and cross-domain changes in complex systems

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ABSTRACT

Government and not-for-profit organizations measure success in terms of their ability to promote an organizational mission. Complex assets in such organizations are acquired in a budget-allocation process which reflects mission priorities. So, complex assets in such an environment must be managed so that availability of the asset is sufficient to support mission objectives as planned. But cost must also be contained within the budget plan, or other mission objectives may suffer. Hence, an objective in such environments is to simultaneously control (1) the risk that percent-availability will fall below a minimum planning threshold α, and control (2) the risk that cost will exceed the planned budget β. This problem is especially difficult because the two risks are negatively correlated.

In this paper we examine this bi-criteria risk minimization problem, for an organization in which the departments (domains) of the organization must compete for scarce resources to achieve organizational objectives. We develop a model that can be used to assess bi-criteria risk of single-domain proposals, and a ranking-and-selection procedure which can be used to choose between those proposals. We then conduct a limited search of solutions which involve linear combinations of the proposals, in order to investigate the potential benefits of 'breaking silos' and 'cooperation' across domains. Results suggest that for complex systems at least, cross-domain solutions are not always superior to single-domain solutions, and that integrated system models are needed to properly evaluate single-domain or cross-domain solutions.

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1. Introduction

In managing productive assets, two key measures of effectiveness are Operational Availability (Ao) – the percentage of time the assets are available for productive operations, and the life cycle cost (LCC) – the net present value of the total ownership cost of the assets, from acquisition through retirement.

In the public sector, LCC is projected and approved in advance (planned and budgeted). Along with LCC, Ao is part of the design criteria of an asset (Hwang, 1996), and projected Ao becomes part of mission planning. Hence, after acquisition is approved and assets are in the field, asset managers have budgets and availability standards which must be maintained. As managing agents (stewards) representing risk-averse taxpayers, or simply to advance their own public sector careers, decision makers may be *primarily* concerned with reducing the risk that cost will exceed the budgeted plan, and reducing the risk that availability will fall below the promised planning threshold. We refer to these criteria as *cost risk* and *readiness risk*. In this paper we assume that good stewardship is synonymous with risk minimization.

The assets we examine in our numerical analysis are hypothetical fighter aircraft, F-XX (Kang & Doerr, 2012). The F-XXs are complex systems which require expenditures for a wide variety of personnel, parts, infrastructure and consumable resources. Their mission performance depends not only on operating personnel, but on the reliability of a collection of components, and a network of maintenance and supply associated with each of those components.

Capturing the LCC of such systems is not a trivial task. There are a large number of important exogenous factors involved, including the capital discount rate, and the price of petroleum, oil and lubricants. There are economies of scale in developing the support infrastructure for training personnel, and maintaining the aircraft. Likewise, modeling the factors which determine the Ao of a system such as the F-XX is daunting. Availability of the system depends on the availability of a number of critical components, each of which has a network of replacement parts and repair processes which must be tracked.

In this paper, we use a simulation model developed over several years as a decision support system to facilitate understanding of

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the relationship between Ao and LCC in a weapon system (Kang, Doerr, Apte, & Boudreau, 2010; Kang, Doerr, & Sanchez, 2006; Kang & McDonald, 2010). We extend that decision support tool to estimate readiness risk and cost risk, and then embed the tool in a search procedure. The search procedure examines a set of process-improvement scenarios to determine a Pareto Set of scenarios which (from the set of proposed solutions) jointly minimize cost risk and readiness risk. Our search procedure, and details of the relevant functional relationships are explained in detail below. The model and risk minimization (selection) procedure are contributions of this paper.

We examine scenarios across four logistics domains: Operations, Maintenance, Supply and Engineering (Re-)design. Each scenario is developed by one domain in isolation, and involves only variables under the control of that domain. We also develop a cross-domain alternative via a numerical search on linear combinations of the single-domain solutions. Our set of single-domain alternatives is developed to represent what have been called ‘silos’ (Lessard & Zaheer, 1996), which sometimes get created by the departments of a large public organization, and which make interdisciplinary efforts more difficult. It is commonly assumed that large savings can be obtained by breaking down these silos, and encouraging better cooperation. Another contribution of this paper is the examination of this assumption. We will show that although it may be true that cross-domain solutions are better, it is not trivially true. That is, single domain solutions may be surprisingly good, and better cross-domain solutions cannot be obtained simply, and perhaps cannot be obtained at all, without a tool such as the one we employ.

In the next section we review the related literature on improving LCC and Ao, the literature on risk management and silos in the public sector, and the literature related to our methodology.

2. Literature review

In this section, we review the literature relevant to our choice of criteria, and the underlying business problem relating to the tradeoff of those criteria. We examine the work that has been done to model closely related business problems. Finally, we briefly review the approaches that have been taken to solving similar bi-criteria risk-minimization problems.

2.1. Criteria

Focus on LCC as an effectiveness metric started at least as long ago as the 1970s, as organizations began to realize that, in the acquisition of technology-based assets, the price of acquisition was a fraction of the total ownership cost (Greenwall, 1977; Lientz, Swanson, & Tompkins, 1978). Recent estimates place Acquisition cost (including RDTE) at an average of 28% of LCC (Boudreau & Naegle, 2005). U.S. Department of Defense (DOD) interest in this metric has been keen from the outset (e.g., Lientz et al., 1978 was funded by the U.S. Office of Naval Research), even though LCC stretches across many budget cycles for most assets. Perhaps this is because some complex weapon systems have cost far more in retrospect than originally planned. The reduction of LCC is a stated DOD priority, and some authors have advocated incorporating LCC as a key design parameter in the initial stages of weapon system development (Boudreau & Naegle, 2005).

While perhaps less well known in the Private Sector, Ao has an even longer history as a key metric in the Public Sector, and the DOD in particular, dating at least as far back as the late 1950s (Bovaird, Goldman, & Slattery, 1962). For non-for-profit organizations, Ao provides a surrogate metric for the profit (benefit) gained through possession of a productive asset (that is, the percentage of time the asset is *available* to support the non-profit mission has been used as a surrogate for the contribution of that asset *to* the mission). Within the U.S. Armed Services, the use of Ao is pervasive, even to the point of measuring labor productivity via its impact on Ao (Horowitz & Sherman, 1980).

Hundreds of papers have been written using either Ao or LCC as criteria: a comprehensive review of either literature is beyond the scope of the current research. The modeling of a bi-criteria tradeoff between availability and cost is more recent. Mostly, these tradeoff models (e.g., Level-of-Repair-Analysis) examine spare inventory levels, and the availability of parts, but they do not incorporate system-level availability as a criterion. Also, these models do not examine LCC at the system level, but rather capture only that part of operations & maintenance cost directly affected by the decision variables they model (i.e., echelon inventory and repair costs). As we will show, such approaches cannot model the impact of operational decisions on *system* cost and availability, because spare parts availability is only part of the determinant of system availability, and operations and maintenance costs are only a part of systems cost. Our goal in this paper is to capture the impact of resource allocation decisions on system availability and system cost *risk*. Large scale simulation models (reviewed in the next subsection) have been built in recent years which capture the system-level tradeoff between LCC and Ao, but these models examine average LCC and Ao as criteria, rather than risk.

2.2. Business problem

As will be detailed in Section 3 of this paper, the Ao of a complex system is determined by several underlying factors for each component of that system. All of these underlying factors are variable, and a complex system has a large number of components (and critical parts within those components), so the modeling of the impact of even one factor (e.g., reliability) on system-wide Ao is a stochastic combinatorial problem. Similarly, the LCC of a complex system is determined by a large number of fixed and variable costs, many of which also affect Ao. Consequently, to our knowledge, no analytical model has ever been developed (or at least, none has ever been solved) which captures both Ao and LCC as optimization criteria in a complex system.

In recent years, analytical cost-based models have appeared to capture some one of the underlying factors of Ao (especially reliability or inventory). An example of this is Majety, Dawande, and Rajgopal (1999) which solved a problem allocating constrained budget dollars to components in order to maximize reliability. Work continues in this vein, for example Coelho (2009) uses a hybrid meta-heuristic/MIP approach to solve a similar problem, while Moreb (2007) solves a deterministic version of the problem using integer programming.

Some work has appeared which optimizes Ao, subject to a cost constraint, or minimizes LCC subject to constraints on Ao. For example, Jin, Yeo, Chung, and Kim (2003) optimize average ‘unavailability’ (1-Ao) of jacketed reactors (used in power generation) subject to a cost constraint using an integer program. Conversely, Bouachera (2012) developed a model to minimize the LCC of gas turbine systems, subject to constraints on Ao.

Descriptive modeling work has appeared, based mostly on large scale simulations, which predicts the Ao and LCC of complex systems. Mostly, this work has been intended for decision support and what-if analysis of particular large scale systems. An early example of this is the work of Stalnaker (1993) who developed a predictive simulation for use at NASA (but made available for general use). Another is the work of Slay et al. (1996) developed on contract for the U.S. Air Force. To our knowledge, neither of these simulations was ever used in formal descriptive research. However, Hwang (1996) developed a simulation model to support the