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An Analytic Portfolio Approach to System of Systems Evolutions

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Abstract

The development of large collections of systems or a 'System-of-Systems (SoS)' is challenging due to the large number of systems involved, complex dynamics attributed to interdependencies between systems, and inherent technical and programmatic uncertainties. The sheer number of decision variables involved in SoS development exceeds the mental faculties of the SoS practitioner, prompting the need for effective analytical support frameworks. Current frameworks and guidelines in addressing SoSE challenges lack analytical means of objective SoS level decision-making. Research in this paper adopts computational decision support methods from financial engineering that allows SoS practitioners the means to identify optimal 'portfolios' of systems based on dimensions of capability, cost and operational risk. The SoS architecture is represented as a hierarchical collection generic nodes that interact to provide the overarching SoS level set of capabilities based on an archetypal set of inter-nodal behaviors. Our research leverages a Conditional Value-at-Risk (CVaR) perspective to managing risks that can incorporate agent based simulation data in the decision-making process. We demonstrate the method using a LCS inspired Naval Warfare Scenario (NWS) as an illustrative case study.

Keywords: system-of-systems, portfolio optimization, value at risk

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1. Introduction

Modern engineering systems have evolved to now encompass large collections of interoperating systems, or a 'System-of-Systems' (SoS), that work cohesively to provide some overarching desired set of capabilities. The constituent systems in the SoS have a hierarchical structure, fall under independent operational and developmental jurisdictions, and have complex interactions due to the many interconnectivities that exist across technical and programmatic dimensions. Typical engineering efforts focus on locally incremental developments and do not explicitly consider their effects within the larger context of the original SoS architecture. Evolving these SoS constructs is a complex endeavor that typically involves the confluence of efforts across multiple stakeholders that work together in developing these large scale collections of systems. Actions of introducing new systems, retiring legacy systems, or implementing various acquisition policies, is fraught with cascading risks that manifest due to system interconnectivities. The result is often inflated costs, delayed schedules, and compromised performance, as evidenced by various program failures. The inherent difficulties in architecting SoS that typically span across multiple domains, and multiple authorities, especially when considering the ubiquity of uncertainties, presents the need for effective analytic tools in minimizing risks, mitigating unnecessary costs, and maximizing SoS level capabilities. These difficulties are further exacerbated by the large number of decision variables involved in developing an SoS architecture; this makes meaningful analysis of an SoS a task that goes well beyond the immediate mental faculties of the SoS practitioner.

The United States Department of Defense (DoD), has released the Defense Acquisitions Guidebook (DAG) (5000 series) [1], System Engineering Guide for System of Systems (SoS-SE) [2] and solicited adaptation of a 'Wave Model' process [3] towards improving SoS acquisition and architecting for the DoD. However, the higher-level articulations in these guides are in need of analytical tools that can quantitatively support SoS level architectural decision-making. Research in this paper is part of a larger body of work funded by the DoD Systems Engineering Research Center (SERC) towards the development of a SoS Analytic Workbench -an effort aimed at reducing the high dimensional complexities of SoS tradespace and providing practitioners with a better informed decision-making environment. The workbench tools do not seek to replace, but rather to complement a SoS practitioner's decision-making process with quantitative insights extracted from characteristics of the SoS tradespace.

This paper in particular focuses on one aspect of the workbench: a portfolio based approach that identifies optimal 'portfolios of interconnected systems based on practitioner's preferences of SoS level capability, cost and acceptable risks. The portfolio formulation extends prior research by the authors that uses robust portfolio optimization techniques to develop SoS architectures [4]. Our current work adopts additional innovations from financial engineering using a 'Conditional Value-at-Risk' perspective as a means of protecting the portfolio from simulated/observable worst case losses in performance or cost. What this more specifically translates to is the mitigation of complex risks that may not normally be easily captured in terms of a typical covariance matrix, as formulated in prior, mean-variance based portfolio formulations. The complex interactions between systems may give rise to complex correlations and changing situations that make it difficult to be represented within the notion of a tailored covariance. Instead, the CVaR based approach more directly addresses the nature of risk (here, loss in performance of the SoS level capability). Our framework leverages performance outputs of agent-based simulation of the operations of an SoS architecture as part of the portfolio formulation.

2. Background and Motivation

2.1. System of Systems

The System of Systems (SoS) paradigm presents a different perspective on how systems need to be categorized and subsequently 'engineered' towards providing some desired overarching capability. The traditional systems engineering paradigm now includes additional consideration for interactive effects with a larger set of dimensions, prompting the development of an alternative taxonomy as defined in reference [5]. In the U.S. Department of Defense, decision-making for SoS architecture development is intuitively represented by the Wave model, as proposed by Dahmann [3] and illustrated in Fig 1.