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Combining Max-Min and Max-Max Approaches for Robust SoS Architecting

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Abstract

A System of Systems (SoS) architecting problem requires creating a selection of systems in order to provide a set of capabilities. SoS architecting finds many applications in military/defense projects. In this paper, we study a multi-objective SoS architecting problem, where the cost of the architecture is minimized while its performance is maximized. The cost of the architecture is the summation of the costs of the systems to be included in the SoS. Similarly, the performance of the architecture is defined as the sum of the performance of the capabilities, where the performance of a capability is the sum of the selected systems' contributions towards its performance. Here, nevertheless, the performance of a system in providing a capability is not known with certainty. To model this uncertainty, we assume that the performance of a system for providing a capability has lower and upper bounds and subject to complete uncertainty, i.e., no information is available about the probability distribution of the performance values. To solve the resulting multi-objective SoS architecting problem with uncertainty, we propose and compare three robust approaches: max-min, max-max, and max-mid. We apply these methods on a military example and numerically compare the results of the different approaches.

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1. Introduction and Literature Review

Many systems are formed from components, which are systems themselves[1]. Formally, we call such a system as System of Systems (SoS) and define it as a collection of the systems that are brought together to provide a predefined set of capabilities[2]. The art of constituting such a system is SoS architecting and this paper addresses a robust SoS architecting problem. SoS architecting has many applications in military, engineering, healthcare, and transportation systems[3,4,5]. This work focuses on a military application of SoS architecting problem. More precisely, we study a multiobjective military SoS architecting problem, where no system can provide the entire set of required capabilities; therefore, the SoS architect selects and connects a subset of the systems so that the SoS architecture can perform all the required capabilities. In doing so, the architect's objectives are to minimize the cost of including and connecting systems and to maximize the performance of the resulting SoS. Similar problems have been investigated in the literature[6,7,8].

In this problem, we define the cost of the SoS architecture, which should be minimized, as the summation of the costs of contributing systems in providing the capabilities and the costs of the connection interfaces among the selected systems. The performance of the SoS architecture is defined as the sum of the performance of capabilities of the included systems in the SoS. However, the performance of a system in providing a capability is not known with certainty. To model this uncertainty, we assume that the performance of a system for providing a capability has lower and upper bounds and subject to complete uncertainty, i.e., no information about the probability distribution of a performance value is given. The paper is organized as follows. In section 2, a formulation of the problem is presented. Section 3 discusses the details of solution methods and Section 4 explains a numerical study. Finally, Section 5 concludes the paper and gives future research directions.

2. Problem Formulation

Suppose that the SoS needs n capabilities such that each of the m available systems can provide some of the capabilities. Let the sets $I = \{1, \dots, n\}$ and $J = \{1, \dots, m\}$ represent the set of capabilities, indexed by i, and the set of systems, indexed by j, respectively. We define $a_{ij} = 1$ if system j provides capability i and $a_{ij} = 0$ otherwise, and $\boldsymbol{A}$ be a $n \times m$ −matrix of a_{ij} values. In addition, let c_{ij} and p_{ij} denote system j's cost and performance of providing capability i, respectively. The SoS architecting problem is to find a subset of the m systems such that all the requested capabilities are presented and the resulting SoS exhibits high performance and low cost.

However, as discussed before the value of p_{ij} is uncertain and no information is available in regard to its probability distribution. As one might know the minimum and maximum values of p_{ij}, we assume that $p_{ij} \in [p_{ij}^l, p_{ij}^u]$. We define decision variables x_j to show whether system j is included in the SoS. If system j is in the SoS, $x_j = 1$, otherwise $x_j = 0$. If two systems are included in the SoS, they should be connected and we show this connection with a binary variable z_{rs}. This variable is equal to one if both systems r and s are included in the SoS and it is zero, otherwise. Let $\boldsymbol{X}$ be a $m \times 1$ −vector of x_j values and $\boldsymbol{Z}$ be a $m \times m$ −matrix of z_{rs} values. We define h_{rs} as the cost of interface between system r and system s.

Here, the decision of the SoS architect is to select systems and connect them. The total cost of architecting a SoS can be calculated as $TC(\boldsymbol{X}, \boldsymbol{Z}) = \sum_{i \in I} \sum_{j \in J} a_{ij} c_{ij} x_j + \sum_{r \in J} \sum_{s \in J, s > r} h_{rs} z_{rs}$, where the first part is the total cost of the selected systems for providing capabilities and the second part is the cost of the interfaces among the selected systems. The total performance of SoS is $TP(\boldsymbol{X}) = \sum_{i \in I} \sum_{j \in J} a_{ij} p_{ij} x_j$ such that $p_{ij} \in [p_{ij}^l, p_{ij}^u]$. Considering total performance as a linear summation of individual performances is a simplistic approach to capture the total performance of a SoS. In practice, linear summation of systems' performances may not be a correct aggregation of the individual performances. Nonetheless, existence of an explicit aggregation function for the total performance is sufficient to formulate the problem as follow and solve it, using any evolutionary technique as presented in this study. Given this, the SoS architecting problem (**SoS-AP**) with the cost minimization and performance maximization objectives reads as follows:

$$
\textbf{SoS-AP} \quad \begin{array}{ll} \max & TP(\boldsymbol{X}) \\ \min & TC(\boldsymbol{X}, \boldsymbol{Z}) \\ s.t. & \sum_{j \in J} a_{ij} x_j \geq 1, \qquad \forall i \in I \end{array} \qquad (1)
$$