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# Enabling Flexibility through Forming and Evolving Systems of Systems

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**Abstract**

Flexibility is a highly desired attribute of many systems operating in changing or uncertain conditions. This paper presents a study of enabling flexibility through designing and operating systems of systems (SoSs). The paper analyzes flexibility mechanisms of SoSs and, accordingly, identifies needs for flexibility that SoSs can meet. Following that, it proposes a hierarchical network as a more flexible SoS architecture for complex or distributed large-scale systems. Then, decision problems for forming and evolving a SoS network are defined. A case that involves integrating distributed renewable energy sources with the main grid is presented to illustrate the implementation of the proposed methodology. Results from this study support the idea of acquiring and maintaining flexibility with SoSs. The paper also identifies research needs for advancing this particular use of SoSs.


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*Keywords:* System of systems, flexibility; dynamics; microgrid; distributed energy sources

## 1. Introduction

Flexibility is a desired attribute of various systems operating in changing or uncertain conditions [1], [2]. Therefore, it has been an important consideration of system design and widely implemented in practice. For example, a production line may be designed to be flexible in switching among product models, or accommodating product

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updates, to respond to changes that may be unknown early in the lifecycle. Nowadays, systems are increasingly more complex or larger than they were used to be, to adapt to the growing and expanding social needs of human beings and rapid technological advancements. The complex architecture of those systems, and the growing importance of embedding flexibility to these systems, make the design and operations of flexible systems a research question for systems engineers.

What flexibility can be created through the design and operations of a system, and how, remain research questions. The current literature on flexibility is largely centered on specific application domains, such as manufacturing flexibility (e.g. [3], [4]), workforce flexibility (e.g. [5], [6]), and others. Despite many successful cases of creating flexibility in various domains, the literature has not been generalized enough to readily support the design and use of flexibility for any engineered systems that are growing in both types and complexity. Moreover, system performance is often characterized by multiple attributes, and flexibility is usually one attribute strongly interdependent of others. Flexibility induces increased or new interactions among systems or system components. Flexibility desired by a system or its elements usually does not naturally exist. The creation and use of the flexibility unavoidably affect other elements or need the collaboration of them. The actual contribution of flexibility to a system is a derivative in that the contribution depends on the evolution of underlying variables driving the needs for flexibility. All the features above make it important to calibrate the flexibility level during the design phase to ensure that the created flexibility is executable and will effectively produce the anticipated benefits later in operations.

This paper is motivated to analyze flexibility mechanisms of systems of systems (SoSs) to propose the adoption of a framework, or hierarchical network, for creating flexibility. The novelty in this paper is the derivation of a strategy for forming and evolving SoSs to provide needed flexibility. Specifically, the study is focused on changes or uncertainty that cannot be handled by a simple system in a cost-effective manner, but by systems of systems (SoSs) [7]. A SoS is a reconfigurable arrangement of independent and useful systems to deliver unique capabilities for a mission [8]. A capability is the ability to execute a specified course of action. It is unlikely the central mission can be accomplished by an individual system. We remark that a SoS is not designed to be a simple collection of systems that each brings one of the required capabilities to the SoS [9], [10]. Five characteristics of SoS distinguished a SoS from a system [11], [12], which are autonomy, belonging, connectivity, diversity, and emergence. The remainder of this paper is organized as the following. The next section briefly summarizes the relevant literature to acknowledge the status of current research. Then, Section 3 presents the proposed framework for enabling flexibility through designing and operating SoSs, followed by an illustrative case that demonstrates the rationale and feasibility of the proposed methodology in real-world applications. Important findings from this study and identified research needs are summarized at the end, in Section 5.

## 2. The Literature

Generally speaking, flexible systems are those that can make changes easily to cope with changes or uncertainty. While it is a desirable characteristic, flexibility is an ambiguous concept. Within the domain of systems engineering, three streams of research efforts have particularly tried to address this issue to improve the communication and capability of designing and analyzing flexible systems among systems engineering practitioners and academics. The first stream of efforts is about defining flexibility (e.g., [1], [2], [13], [14], [15]). These studies all emphasized the critical aspects of flexibility including the existence of needs for flexibility, flexibility mechanisms, and effects of flexibility. The second stream has been focused on measuring and quantifying flexibility (e.g., [14], [16], [17], [18]). The degree to which changes can be made to a system's architecture is a way of quantifying flexibility [16], [19], [20]. Metrics for flexibility have been developed based on system's architecture and used to measure the flexibility of generic system architectures [20]. The third stream studied the interdependence of flexibility with other attributes of systems (e.g., [16], [21], [22]), and the impact of flexibility on system capabilities, performance, and others (e.g., [2], [13], [16]). All these efforts have built a foundation for the study in this paper.

A few research papers explicitly studied the flexibility of SoSs. Gorod et al. [23] examined the flexibility of a SoS as the flexibility of autonomy, flexibility of belongs, flexibility of connectivity, flexibility of emergency, and flexibility of diversity. They developed a concept of flexibility dynamic in their study. Recently, Dagli, et al. [24] led a series of research for developing flexible and intelligent learning architectures for SoSs.