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Enabling System of Systems Analysis of Critical Infrastructure Behaviors

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Abstract Critical infrastructures are highly complex collections of people, processes, technologies, and information; they are also highly interdependent where disruptions to one infrastructure commonly cascade in scope and escalate in impact across other infrastructures. While it is unlikely that disruptions can be prevented with certainty, an effective practice of critical infrastructure analysis can reduce their frequency and/or lessen their impact. We contend that proper critical infrastructure analysis necessitates a *system of systems* approach. In this paper, we identify requirements for integrated modeling and simulation of critical infrastructures. We also present our integrated modeling and simulation framework based on a service-oriented architecture that enables system of systems analysis of such infrastructures.

1 Introduction

Critical infrastructures are those systems or assets (e.g., electric power and telecommunication systems, hospitals) that are essential to a nation's security, economy, public health, and/or way of life [9]. The blackout in the northeast United States and southeast Canada in 2003, the hurricane damage in Louisiana and Texas in 2005, and numerous other smaller scale occurrences demonstrate the potentially catastrophic impacts of critical infrastructure disruptions. While it is unlikely that disruptions can be prevented with certainty, an effective practice of critical infrastructure analysis can reduce their frequency and/or lessen their impact by improving vulnerability assessments, protection planning, and strategies for response and recovery.

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In [17], it is argued that proper critical infrastructure analysis must account for the *situated* nature of infrastructures by incorporating into analysis the spatial, temporal, and functional context of each infrastructure. It is also argued that proper critical infrastructure analysis must account for the *multi-dimensional* nature of infrastructures by accounting for both the engineering and behavioral properties of each infrastructure. Engineering properties are the underlying physics-based properties that shape and constrain the operation of an infrastructure. Behavioral properties are the relational properties that emerge from business processes, decision points, human interventions, participating information, etc. of an infrastructure.[1]

These two characteristics contribute to making critical infrastructure analysis a "wicked problem" [15]. Wicked problems are non-linear problems that are without definitive formulations. Such problems have an open solution space where solutions have relative quality. Furthermore, each problem instance is arguably unique. We contend that the situated and multi-dimensional natures of critical infrastructures and the "wickedness" they introduce to analysis necessitate a *system of systems* approach to critical infrastructure analysis.

System of systems analysis is appropriate for understanding large-scale, highly complex phenomena that are comprised of highly interdependent participating systems, which themselves may be large-scale and highly complex. Such a phenomenon is described as a *system of systems* when the behavior of the *system* is reflected in the emergent, synergistic behaviors of the participating *systems*. Critical infrastructure systems possess these characteristics as each infrastructure system is a highly complex collection of people, processes, technologies, and information. In addition, critical infrastructures are highly interdependent where disruptions in one infrastructure commonly cascade in scope and escalate in impact across other infrastructures [14]. As such, to analyze one of these infrastructures properly requires a system of systems analysis of all of these infrastructures.

To meet this challenge, *integrated modeling and simulation* has emerged as a promising methodology to support system of systems analysis of critical infrastructures. However, integrated modeling and simulation necessitates both: 1) a proper representation of the situated, multi-dimensional nature of critical infrastructures; and 2) a proper integration framework and methodology for system of systems analysis. In [17], a representation of infrastructure context and behavior for integrated modeling and simulation is presented. In this paper, however, we examine the latter issue, the challenge of designing a proper integration framework for the modeling and simulation of critical infrastructures.

The primary contributions of the work reported here are: 1) we identify emerging integrated modeling and simulation requirements for system of systems analysis of critical infrastructures; 2) we demonstrate the application of a service-oriented architecture to the challenge of integrated modeling and simulation of critical infrastructures; and, 3) we illustrate how this framework enables system of systems analysis of critical infrastructures.

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[1] Casalicchio et. al. [2] provide an analogous description of the situated and multi-dimensional natures of critical infrastructures to that found in [17] in their discussion of the horizontal and vertical partitioning of federated models.

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The structure of this paper is as follows. We begin by exploring related work in critical infrastructure modeling and simulation. Next, we examine emerging requirements for integrated modeling and simulation of critical infrastructures. We then present our framework for integrated modeling and simulation based on the popular service-oriented architecture. We conclude by providing an illustration that demonstrates system of systems analysis of critical infrastructures using our framework. Lastly, we provide a summary and discuss future work.

2 Related Work

Numerous approaches to critical infrastructure modeling and simulation have been explored. A comprehensive survey conducted in 2006 of current solutions highlights several of these approaches [11]. One approach to critical infrastructure modeling and simulation is to focus analysis to the exploration of single, isolated infrastructures, e.g., [1, 4, 13]. However, this non-integrated approach to modeling and simulation fails to recognize the situated nature of critical infrastructures. Furthermore, this approach does not offer a generalized way to fuse independent analyses.

Another approach to critical infrastructure modeling and simulation is to focus on the interdependencies among infrastructures, e.g., [5, 7]. Though not an integrated approach to modeling and simulation, this approach recognizes the situated nature of critical infrastructures. However, this approach does not adequately incorporate into the analysis the underlying multi-dimensional nature of each infrastructure. While dependencies among critical infrastructures can lead to cascading effects with escalating impacts [14], such effects and impacts often emerge from the interplay between these dependencies and the multi-dimensional behavior of each infrastructure. By focusing only on infrastructure interdependencies, the fidelity of the analysis is greatly reduced.

Still another approach to critical infrastructure modeling and simulation is to build comprehensive models of critical infrastructures, e.g., [3, 6, 8, 14, 16]. However, this approach is not necessarily tractable due to the unique characteristics of each infrastructure. As a result, comprehensive models typically emphasize high level analysis.

Finally, a more recent approach to critical infrastructure modeling and simulation focuses on the development of what Pederson et. al. [11] describe as a coupled modeling approach, e.g., [2, 17, 18]. Under this approach, individual infrastructure models are integrated in a generalized way with models of infrastructure dependencies to enable system of systems analysis - thus, coupling the fidelity of individual infrastructure models with the requirement for situated analysis.

The promise of a coupled approach to critical infrastructure modeling and simulation highlights the challenge of designing a proper integration framework. Specifications for such frameworks have been developed. For example, the IEEE Standard 1516 High-Level Architecture (HLA) for modeling and simulation presents one such specification. The HLA specification is comprised of federates (which

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could model individual infrastructures), an object model (which defines a vocabulary for discourse among federates), and a run-time interface and infrastructure (which enable interaction among federates).

3 Modeling and Simulation Requirements for System of Systems Analysis of Critical Infrastructures

Enabling system of systems analysis of critical infrastructures presents many challenges. We describe a specific set of these challenges by identifying associated requirements for integrated modeling and simulation of critical infrastructures.

Requirement #1: *Modeling and simulation solutions for critical infrastructure analysis should provide a generalized approach to model integration.* Critical infrastructure analysis requires the participation of a dynamic set of infrastructure models. Evolving analysis requirements will necessitate the plug-n-play of different representations of the same infrastructure as well as different collections of infrastructure models. Requirement #1 highlights the importance of a uniform approach to model integration to account for changing requirements.

Requirement #2: *Modeling and simulation solutions for critical infrastructure analysis should provide a generalized method for infrastructure model discovery.* Critical infrastructure analysis is shaped not only by evolving requirements, but also by infrastructure model availability. Requirement #2 emphasizes the need for a uniform approach to discover infrastructure models to afford this dynamism.

Requirement #3: *Modeling and simulation solutions for critical infrastructure analysis should provide a generalized method for infrastructure model configuration.* Often critical infrastructure models are not static representations, but are configurable to afford a range of behaviors for comparative analysis, to address issues of precision, and to manage computation and performance tradeoffs. Requirement #3 articulates the need for a generalized approach to configure the parameterized aspects of infrastructure models.

Requirement #4: *Modeling and simulation solutions for critical infrastructure analysis should provide a method for infrastructure model mapping and mediation.* Critical infrastructures are highly interdependent. Events within one infrastructure produce effects within other infrastructures. As such, requirement #4 highlights the importance of a uniform approach to mapping and mediating interactions among models so that a method that accounts for dependencies across infrastructures can be afforded.

Requirement #5: *Modeling and simulation solutions for critical infrastructure analysis should provide a method for supporting emergent critical infrastructure behaviors.* Situating critical infrastructure analysis requires more than the ability to link infrastructure models. Properly situating analysis also requires a method for supporting emergent critical infrastructure behaviors. These behaviors are not present within individual infrastructures; nor do they emerge due to simple cross-infrastructure dependencies. Rather, these behaviors appear from the synergy of interacting infrastructures.

Requirement #6: *Modeling and simulation solutions for critical infrastructure analysis should provide a method for registering interest in temporal events and model events.* Events within one infrastructure often produce effects within other infrastructures. To mediate this interplay, a method for registering interest in model events is required. In addition, infrastructure behavior may vary with time - e.g., energy demands at 3:00pm on a hot summer day are different than at 2:00am on a cool spring night. As such, a method to make infrastructure models temporally aware is required.

Requirement #7: *Modeling and simulation solutions for critical infrastructure analysis should provide a method for accommodating differing simulation methodologies.* Different infrastructure models may leverage different simulation methodologies. For example, some models leverage a discrete simulation methodology while other models leverage a continuous simulation methodology. Requirement #7 highlights the necessity for an approach to mediate the differences among simulation methodologies.

4 A Service-Oriented Framework for Integrated Modeling and Simulation

Given the diversity and complexity of individual infrastructure models, we contend a key to enabling integrated modeling and simulation of critical infrastructures is simplicity in the design of an integration framework. Service-oriented architectures (SOAs) embody this simplicity and provide a promising approach to integrated modeling and simulation. SOAs are an emerging approach for enterprise application design and business function integration [10, 12]. Structurally, such architectures are characterized by three component roles: service providers, service requesters, and service registries. *Service providers* implement some business functionality and expose this functionality through a public interface. *Service requesters* leverage needed business functionality through these public interfaces. *Service registries* broker the discovery of business functionality by service requesters.

Functionally, SOAs are characterized by two distinct mechanisms: mechanisms that facilitate business function registration/discovery; and mechanisms that exercise business functions through requester/provider interaction (see Fig. 1). SOAs are also known for their configurability, extensibility, and scalability. SOAs enable with greater ease the dynamic aggregation of different functionality (i.e., configurability); they facilitate with greater ease the introduction of new functionality (i.e., extensibility); and, they accommodate with greater ease various numbers of providers, requesters, and registries (i.e., scalability).

Given these characteristics, the simplicity of the SOA design, and the aforementioned modeling and simulation requirements, SOAs serve as the design foundation for our integrated modeling and simulation framework to enable system of systems

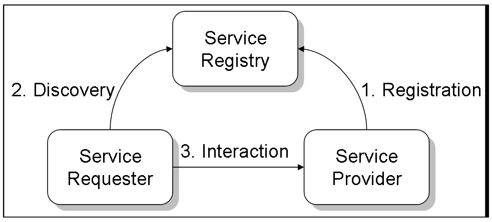

Fig. 1 Service-Oriented Architecture.

analysis of critical infrastructures. Our framework is highlighted by four important design elements: 1) the instantiation of the SOA component roles; 2) a common service provider interface (SPI); 3) the service registration and discover method; and 4) the simulation execution protocol. Collectively, these design elements address to varying degrees the identified modeling and simulation requirements.

4.1 SOA Component Roles

As previously described, SOAs are comprised of three component roles: service providers, service requesters, and service registries. Within our integrated modeling and simulation framework, individual infrastructure models function as our service providers. Our Integrated Modeling Environment (IME) functions in the role of service requester. The service registry is enabled by a configuration file and the underlying file system (see Fig. 2).

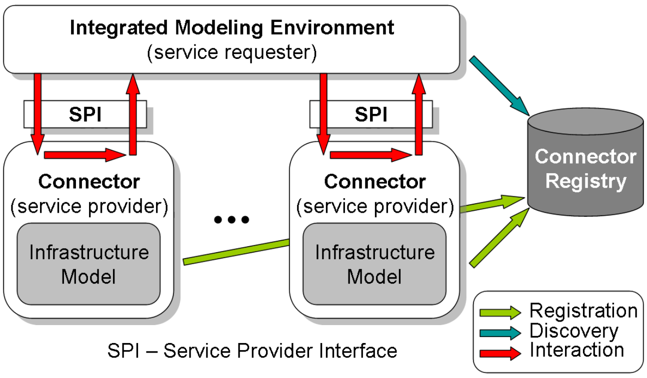

Fig. 2 Integrated Modeling and Simulation Framework.

Service providers participate in multi-infrastructure simulations by implementing a Connector that realizes the common SPI. This allows the service requesters, to interact with all infrastructure models using a common interface. Given, how-

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ever, that infrastructure models are often configurable, e.g., PowerWorld Simulator [13] allows end users to select different solvers, each Connector may define the set of configurable properties. Configurable properties must be assigned a valid value before a Connector, and the infrastructure model it represents, can participate in multi-infrastructure simulations. Together, the common SPI and Connector properties provide a generalized approach for infrastructure model interaction, while enabling infrastructure model configuration, i.e., Requirements #1 and #3.

4.2 Service Registration and Discovery Method

To participate in integrated simulations, infrastructure models must register with our framework. First, service providers add entries for their infrastructure models to a configuration file and place relevant software assemblies in specified file directories. The configuration file and supporting file directories provide the IME a means to discover infrastructure models automatically, i.e., Requirement #2. Next, service providers expose their infrastructure model data to the IME. This is occurs for several reasons: development of a common intermediate representation is needed in order to support the specification of cross-infrastructure dependencies, i.e., Requirement #4; awareness of these data facilitate support for emergent infrastructure behaviors, i.e., Requirement #5; and exposing relevant infrastructure data enables the IME to generate a unified visualization for the region of interest. Infrastructure model registration and discovery concludes with the IME possessing a set of Connectors where each Connector encapsulates access to an infrastructure model.

4.3 Common Service Provider Interface

Interaction with infrastructure models presents a special challenges to integrated simulations. First, to address the need for a generalized approach to model integration, i.e., Requirement #1, our framework defines a common SPI for all infrastructure models. The simplicity of our common SPI is one aspect of our framework that distinguishes it from the HLA by reducing the complexity of Connector/federate design. The common SPI also allows infrastructure models to register interest in selected temporal events and model events, i.e., Requirement #6. In the following, we introduce the common SPI.

Connect(); When a user wishes to conduct system of systems analysis of critical infrastructures by means of multi-infrastructure simulations, the IME (i.e., service requester) “connects” to all enabled Connectors. The connection process accomplishes two things. First, it initializes each infrastructure model with a timestamp indicating the simulation start time. Second, it allows each infrastructure model in response to register interest in relevant temporal events and model events, i.e., Requirement #6.

Disconnect(); When a simulation is complete, the IME "disconnects" from the participating infrastructure models.

GetState(); Before a simulation begins, the IME requests from each infrastructure model the operational state of infrastructure components. This interaction between the IME and the infrastructure models synchronizes the state of IME data with each infrastructure model. In response to a GetState() request, an infrastructure model will report to the IME the requested state attributes for the requested infrastructure features.

SetState(); When infrastructure models or the IME model of infrastructure dependencies indicate that the state of an infrastructure feature should change (i.e., disabled to enabled; or, enabled to disabled), the SetState() operation is invoked on the relevant infrastructure model. In response, an infrastructure model will report the plausible effects of the state change as a set of subsequent change events. These events are scheduled in the IME simulation timeline for processing.

ClockAdvanceRequest(); This functionality is required due to the behavior of some infrastructure models. Some infrastructure models require, as much as possible, that all change events for a given timestamp be processed in batch. Thus, when the IME has processed all events associated with the current time on the simulation clock, each infrastructure model is notified and a request is made for approval to advance the time clock. In response, an infrastructure model returns the plausible effects of queued events as a set of subsequent change events. These events are scheduled in the IME simulation timeline for future processing.

AdvanceClock(); When the simulation time clock reaches a relevant temporal event, interested infrastructure models are notified of this event using the AdvanceClock() operation.

4.4 Simulation Execution Protocol

The simulation execution protocol supported by the integrated modeling and simulation framework enables event-driven, i.e., discrete, simulations. The IME as service requester, maintains a simulation clock and an ordered simulation timeline of events. The IME also realizes the following simulation execution protocol. At the beginning of a simulation, the IME connects, via the Connect() operation, to each enabled Connector, i.e., infrastructure model. Each Connector responds with infrastructure and temporal events of interest. Next, the IME synchronizes its state with each infrastructure model using the GetState() operation.

Every simulation is associated with a course of action (COA). A COA identifies the infrastructure events that are "scheduled" to occur during the simulation. These events are inserted into the simulation timeline. Thus, in the timeline there may be three types of events: scheduled infrastructure events (called actions), emergent infrastructure events (resulting from event processing), and temporal events.

Simulation execution begins by processing the "current" events. Processing either a scheduled or emergent event, involves two parts. First, state change is affected

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in the relevant infrastructure model using the SetState() operation. This operation will return a list of emergent events which are properly inserted into the simulation timeline by the IME. If state change is not affected because the relevant infrastructure model already possesses the desired state, the event is retained but processing of the event terminates. Second, if the event results in a state change, then the infrastructure event is processed according to the relational model specified in the IME context and behavior ontology [17]. Processing a temporal event requires the IME to use the AdvanceClock() operation to notify interested infrastructure models.

Once all "current" events have been processed, the IME interacts with each infrastructure model using the RequestAdvanceClock() operation to request approval for the advancement of the simulation clock. If no new "current" events are generated from these requests, then the simulation clock is advanced to next timestamp when either a scheduled, emergent, or temporal event is to occur. When no unprocessed events remain in the simulation timeline, the IME disconnects from each infrastructure model using the Disconnect() operation; and the simulation terminates.

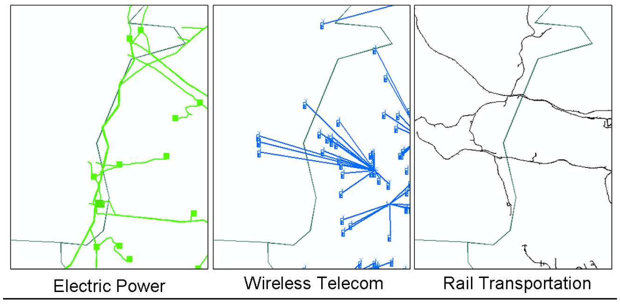
While this framework supports discrete simulations, its design does not necessarily prevent the integration of infrastructure models that support continuous simulations. This is possible because the IME "knows" about infrastructure models only by the common SPI. Thus, the framework encapsulates infrastructure model behavior in a manner that hides the service provider simulation methodology, e.g., discrete or continuous, from service requesters. As such, continuous simulations can be embedded within multi-infrastructure discrete simulations. For example, using our framework we have integrated into multi-infrastructure discrete simulations electric power simulations, supported using PowerWorld Simulator, which uses a continuous simulation approach. Thus, the design of the SPI and the encapsulation of infrastructure models, provide an approach to address Requirement #7.

The simulation execution protocol is another aspect that distinguishes our framework from the HLA. While the HLA is designed to allow a full range of distributed interaction among federates including both synchronous and asynchronous interaction, our integration framework centralizes interaction through the IME using a well-defined synchronous interaction protocol. Furthermore, the IME centralizes management of the simulation clock. While these characteristics restrict the range of interaction among Connectors, we believe the simplicity of this design and the common SPI will increase the usability and utility of the integration framework.

5 Illustration

To demonstrate how our framework for integrated modeling and simulation enables system of systems analysis of critical infrastructures, an illustration is provided. This illustration focuses on an urban region, possessing infrastructures for electric power, telecommunication, and rail transportation (see Fig. 3).

In this illustration, independent models for electric power, telecommunication, and rail transportation have been incorporated into our framework as service providers.



Electric Power Wireless Telecom Rail Transportation

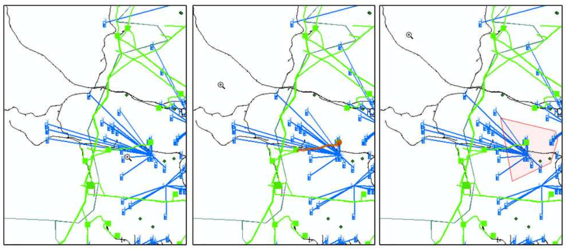
Fig. 3 Illustrative Infrastructure Models.

In other words, a Connector that realizes the common SPI has been implemented for each infrastructure model. Using the IME ontology for infrastructure context and behavior [17], temporal, spatial and functional relationships within and among the infrastructure models are also specified.

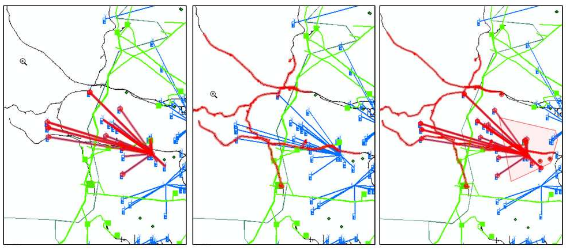
Fig. 4 depicts the order of effect for an illustrative multi-infrastructure simulation. The initial state of this simulation has all three participating infrastructures enabled. The course of action for this simulation includes one scheduled event - a fallen power line, i.e., 1^{st} order effect. Loss of this power line leads to a power outage in the specified region, i.e., 2^{nd} order effect. This power outage forces a telecommunications central office to migrate to backup power. After backup power is exhausted, however, the central office is disabled, which, in turn, disables connected wireless towers, i.e., 3^{rd} order effect. The subsequent loss of telecommunications affects rail transportation as indicated since the rail infrastructure depends on the telecommunication infrastructure to operate rail switches, i.e., 4^{th} order effect. The simulation final state is also shown.

Once simulations complete, they may be explored, replayed, and saved for further analysis. Using the IME, users can examine the order-of-impact of events as well as the plausible impact to each critical infrastructure. In addition, users can examine the event trace to understand and/or validate the event chain that led to an effect. During analysis, users may refine the infrastructure context and behavior ontology, reconfigure infrastructure models, and add/remove/plug-n-play different infrastructure models to explore "what-if" scenarios.

For this illustration, three infrastructure models were integrated using our SOA framework for integrated modeling and simulation. Due to obvious data sensitivities, notional data were intermixed with actual data. To date, we have used our framework to integrate numerous infrastructure models including models supported by 3^{rd} party solutions such as PowerWorld Simulator [13] and Network Analyst [1]. We have also developed a toolkit of Connectors to enable rapid prototyping of infrastructure models (no Connector development required), which is useful when model data are relatively sparse. The resulting models, however, are still known to the IME only through the common SPI. Finally, we have coupled continuous infrastructure simulations, e.g., [13], into discrete multi-infrastructures simulations.



Initial 1st Order 2nd Order



3rd Order 4th Order Combined Effects

Fig. 4 Illustrative Multi-infrastructure Simulation.

6 Conclusion

Our framework for integrated modeling and simulation is actively being used to explore and analyze critical infrastructures for large scale ($>$100,000 km^2) geographic regions. In addition, we have developed integrated models for urban regions of various scales (e.g., $>$500 mi^2, 1000 acres). We have also demonstrated the IME on a corporate IT infrastructure model for a Fortune 100 company integrating models for IT hardware, system software, business applications, business processes, and business units. Verification and validation is further enabled by our adherence to the underlying principle of transparency. Analysis enabled by our framework is transparent to the analyst. Event traces can be explored and questioned by subject matter experts. In fact, this practice is regularly utilized by our user community.

At the same time, there are aspects of our framework that require further investigation. First, the robustness of our common SPI and simulation execution protocol must be examined. The SPI and simulation execution protocol have undergone some revisions since their initial design to address emergent requirements of individual infrastructures models. For example, the ClockAdvanceRequest() was introduced after discovering that some infrastructure models require, as much as possible, that all change events for a given timestamp be processed in batch. Second, Connector developers are currently responsible for mapping infrastructure model data into a common intermediate representation. This increases the complexity of Connector development while simplifying the design of the IME. Further study is required to determine and validate the proper balance of this responsibility between the Con-

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nector developer and the IME. Third, further research is required to validate the integrated modeling and simulation requirements identified in Section 3. These requirements emerged through both research and practice. Additional research is required to determine the completeness and appropriateness of this set. Finally, formal study of the scalability and complexity of our framework from a cognitive perspective is required. That is, a better understanding is needed of how our framework impacts (positively and/or negatively) the cognitive limitations of the developers of integrated models for system of systems analysis.

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