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Systems-of-Systems Engineering and the Pragmatics of Demand

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Abstract *- Systems of systems that manage health care or enable Albert's "power to the edge" are expected to provide the flexibility to engage multiple enterprises in innovative, collaborative, ways to solve problems. This paper describes a systems engineering approach to engineer infrastructure that will support the restriction of systems of systems behavior at the time of use rather than at design time. We present a process for describing demands within their context of use, and how organizational variations in collaborative approaches (geometries-of-use) can be related to variations in these demands-in-context (pragmatics), thus giving a way to engineer a systems-of-systems' agility i.e. its ability to adapt to changing demands.*

Keywords *- agility, geometries of use, pragmatics, synchronization, Systems of Systems*

1 INTRODUCTION

Traditional systems engineering makes the simplifying assumption that the systems are well bounded and therefore immune from disturbances (demands) that are not accounted for in the engineering process [1]. These systems manifest capabilities that are specified during system design. However, complex systems of systems not only frequently violate this assumption, but also are increasingly expected to react to demands that require unanticipated forms of interoperability among their constituent systems. Such systems of systems are unbounded—subject to demands that can never fully be accounted—and enable their users to compose capabilities by orchestrating and synchronizing their constituent systems at or near the time of use. Examples are the complex systems of systems used in the management of health care or to support military commanders in the field taking "power to the edge" [2].

Advancements are being made in a new systems engineering approach that promotes collaborative composition by enabling systems-of-systems behavior to be specified or restricted close to the time of use rather than at design time. Enterprises such as symphony orchestras expect this behavior from their musicians in the same way that today's military commanders in the field expect it from the military capabilities available to them. As a "social system," the composer's relationship to the musicians directly parallels the socio-technical system that the military commander calls on to generate composite capabilities. In a very real sense we want to enable these socio-technical systems to be more and more responsive to the dynamic nature of the demands placed upon them; striving to increase their ability to be dynamically responsive to demands for changing forms of interoperability.

We present here a process for describing demands within their context of use, which we refer to as the pragmatics of demand. We describe how variations in compositional approaches can be related to pragmatic variations in these demands-in-context, thus giving a way to analyze a systems-of-systems' ability to support a variety of forms of demand—that is, to exhibit agility. The units of analysis for this process are the different forms of interoperability being demanded of a complex system of systems, which we refer to as geometries-of-use. This in turn provides a way to reason about

- functional granularity—balancing setup and overhead costs with runtime delivered value
- system components coupling—making explicit the behavioral aspects that traditionally require implicit knowledge of the components' internal workings
- the variety of forms of orchestration[1] and synchronization required

The sections of this paper address what the pragmatics of demand are, where and when they are defined, how they can be used to shape our thinking, and how they relate to the compositional approaches needed for systems of systems. We illustrate through examples how complex environments can be stratified, modeled, and analyzed to facilitate improvements in their agility.

[1] **"Orchestration" verses "Choreography"** As [13] points out "Sometimes, the term ['choreography' is] used. For example, while [11] uses the term 'choreography' for exploiting a BPEL based flow engine, [12] uses the term 'orchestration' instead." In our opinion, orchestration allows us to address explicitly the effects of interoperation between different instruments as well as the through-time sequencing of notes; in contrast, our laymen's impression of choreography (with apologies to the choreographers in our readership) only addresses the latter, i.e. movements.

2 THE PRAGMATICS OF DEMAND

As interoperability among computer systems has become more important, so has the quest for more sophisticated forms of interoperability.

Figure 1 from the US Department of Defense (DoD) Enterprise Architecture Technical Reference Model [v0.04 dated 20 August 2005, http://www.defenselink.mil/cio-nii/docs/DOD_TRM_V0.4_10Aug.pdf] illustrates the U.S. DoD perception of the evolution from monolithic to component-based solutions, embracing real-time environments, virtual organizations, distributed functions, and component/service oriented architectures.

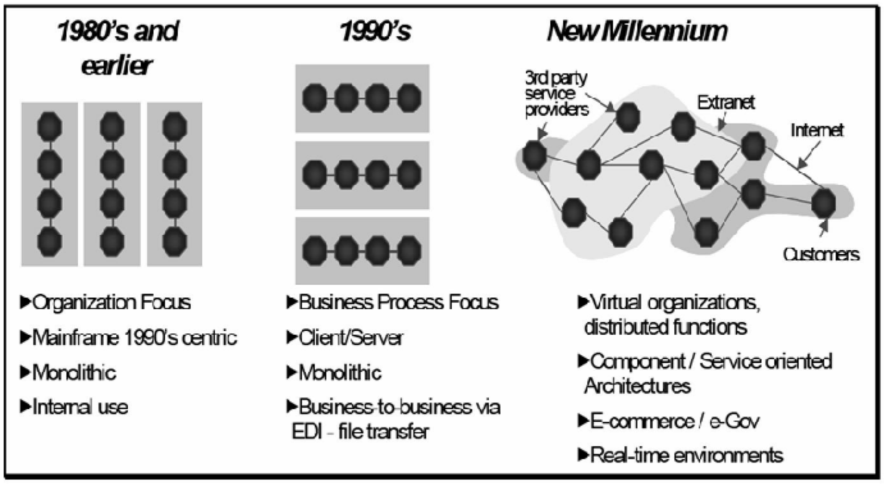


Fig. 1: Evolution of Monolithic and Component-Based Solutions

Such "New Millennium" systems of systems are essentially socio-technical in nature and are expected to provide the flexibility to allow multiple enterprises to employ innovative ways to solve problems. One example of the sort of technical environment supporting these systems of systems is the Global Information Grid (GIG) being developed by the U.S. DoD.

There has been a steady progression of syntactic and semantic developments that have increased our ability to rapidly share data in our present day web enabled environments. We have achieved the ability to transport (with payload transparency) and present (hyper-text that self describes presentation requirements) textual and graphics data across multiple platforms for the man-machine interface. Advancements continue in the more challenging space of machine to machine interoperability with such efforts as the semantic web and OWL-S [3] [4] [5] [6]. These efforts are working to enable machine to machine self description of meaning and expected shared behavior. But "semantics" here refers to meaning defined in terms of machine behaviors. What happens when we embed these approaches within socio-technical systems? We believe an expanded approach to semantics is needed that can consider the specific socio-technical context in which interoperability between systems is being demanded by users and that can take into account the effect that the context in which those users are operating has on the way systems need to be orchestrated and synchronized. This expanded approach involves considering what we call the pragmatics of demand.

3 CHARACTERIZING THE PRAGMATICS OF DEMAND

The pragmatics of demand is a way of understanding how demand for some forms of interoperation can only be known from the context in which that interoperation must generate effects. These forms of demand are encountered particularly where systems of systems are intended to support a wide range of behaviors, only some of which can be defined ahead of time. To respond to these forms of demand, the systems-of-systems engineer must build individual systems that are able to interoperate in different ways within a wide variety of situations. Recognizing that this flexibility may add cost to constituent systems, our approach also helps the engineer to reason about the tradeoffs between constituent cost deltas and the value of increased flexibility.

The GIG is one part of such a systems-of-systems environment. The GIG is intended to provide the infrastructure and capabilities required to support the U.S military in a broad range of operations including warfighting, peacekeeping, and humanitarian operations, all of which may be conducted within or outside of coalitions. A key requirement for the GIG is to support a wide range of independent behaviors through the way individual systems can be orchestrated to create composite capabilities which can in turn be synchronized to generate desired effects.

Consider a composer[2] who wants to produce a particular emotional effect in his audience. To deliver a composition as

[2] We hope that our musician readers will forgive our laymen's analogy into their domain; we know that we have not used all the musical terminology

a performance, he needs to orchestrate the behaviors of different instruments and define how those behaviors are to be synchronized (by a conductor if an orchestra, self-synchronized if a string quartet). To do this, he needs to:

- know enough about the potential behaviors of each instrument to be able to describe the particular sounds he needs from each one and
- be able to write that down (produce a score of musical parts) in such a way that each musician (including the conductor) can perform his or her part.

Of course all these elements of a performance (musical parts, conductor, music, audience) become much less well differentiated when playing jazz, because the performance is emergent among the musicians, rather than being an interpretation of a previously defined composition.[3] Nevertheless, even when the musicians do not improvise, the performance comes out different each time because of the particular pragmatics of the situation in which the performance takes place.

Lewis et al [13] describe four layers in the way machines are used by organizations. The point they make is that standards are effective in Layers 1 and 2, but are only just beginning to address Layer 3.

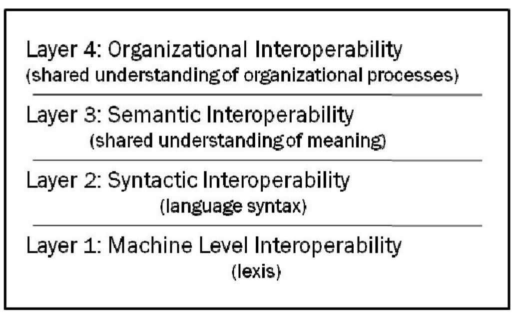


Fig. 2: Layers of interoperability

These layers can be illustrated using our musical example. Each instrument has its particular way of making sounds (lexis) that are organized by the particular technique needed for playing the instrument (syntax). The way the instrument is actually played then gives us our semantic level, where the behavior of the instrument is restricted to a subset of its behavioral semantics, all the possible sequences and combinations of sound that the instrument is able to make. If we were only interested in the behavior of machines, we could stop here, but in a complex system of systems, we are dealing with a socio-technical system that must include the way the use of technical systems interoperates with other users. Thus the behavior of each instrument is dynamically customized by its player, and the ensemble of instruments playing together is an orchestration of their dynamically customized behaviors (the organizational level)

But as we know, each performance is different, producing a different effect on its audience. Thus we still need layers to describe the particular way the conductor synchronizes the performance, defining a *pragmatics*, and the particular ways the performance is experienced by the audience are the performance *effects*. This gives six layers in total as illustrated in Figure 3.

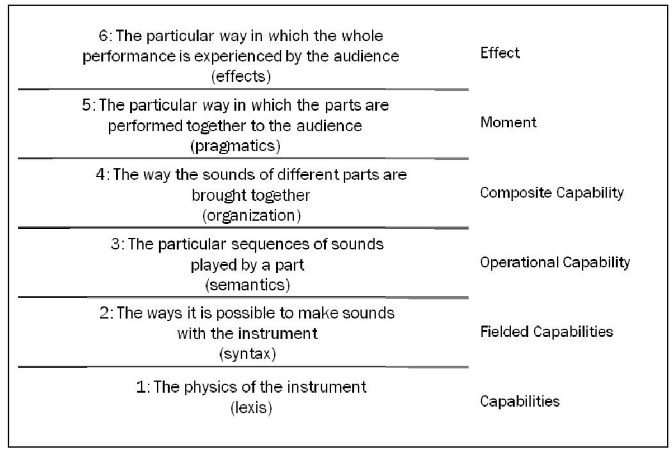


Fig. 3: Stratification Layers

Noteworthy and giving evidence to the existence of these layers is the fact that attributes at any of these layers can significantly alter the final effect. From mechanical failure of an instrument to the musicians' skills to the conductor's interpretation to the audience's receptivity—all can have significant impacts on the resulting effects.

Returning to our GIG example, technology (lexis) allows us to build systems that offer some repertoire of behaviors (syntax). These bottom two layers define a behavioral semantics representing all the possible behaviors of the system. In practice, people only use a subset of these in a socio-technical system, dynamically customizing the behavior of systems to create operational capabilities (semantics). The use of these constituent operational capabilities are then orchestrated to form composite capabilities (organization), and the way all these operational capabilities come together as a composite capability in the middle two layers defines the socio-technical semantics defined for a particular fielded force. The top two layers then define the way the use of these orchestrated capabilities are synchronized in relation to the intended recipients of those behaviors (the pragmatics), producing effects on the recipients. It is this particular synchronized performance of the system of systems in relation to its intended recipients that defines the pragmatics of demand.

correctly and would welcome any improvements from the music theorists in the readership.

[3] We realize that a jazz composer expects an emergent performance, so in that respect whatever happens is somewhat "intended." We might, perhaps, think of jazz musicians as the special forces of the musical world!

4 HOW PRAGMATICS OF DEMAND SHAPES OUR THINKING

If you listen to music critics, you will have heard them break down a performance (alias a synchronization) into a number of moments which for them are decisive in characterizing the effects of the performance. These moments will involve passages of greater or lesser duration, and will be of greater or lesser moment in determining the effects of the performance as the critic judges it.[4] They comprise decisive moments in the critic's judgment of the overall effect of the performance on the audience.

In our GIG example, a commander's intent will operate something like that of the conductor performing a new composition—the intent is to generate particular effects on the intended recipients of the performance. The campaign plan describes how the commander intends to create a number of decisive moments that demand mission performances synchronized in such a way as to produce the intended overall effect on the recipients.

Each decisive moment will involve its own particular sequence of events that involve some synchronization of composite capabilities that must be built out of lower-level operational capabilities (or force elements).[5]

Force commanders will have their own particular assumptions about how to use the force elements at their disposal, which will be bound up with the way they want to orchestrate and synchronize the mission behaviors they need for their campaign plan. But implicit in these orchestrated composite capabilities, however named, will be particular geometries of use defined in terms of the particular forms of interoperation and cooperation needed between constituent operational capabilities. In Figure 4, we see how the same six layers in Figure 3 are brought into relation with each other in the context of generating military effects. The generation and analysis of these cascading matrices as part of a socio-technical system of systems model is a key aspect of our engineering approach.

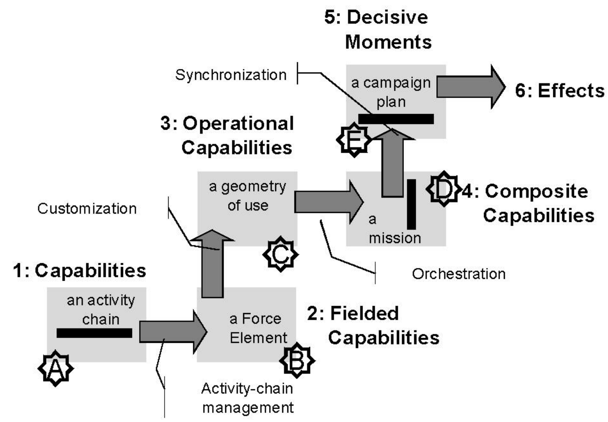


Fig. 4: Composition to Achieve Effects

5 PRAGMATICS OF DEMAND AND COMPOSITION

From here it is a short step to ask two questions: (1) how do we define the requisite variety of geometries-of-use needed to enable force commanders to generate the effects they need across the range of scenarios that they are being asked to confront and (2) what is the ability of the infrastructure of constituent capabilities to support that variety?

To define the requisite variety of geometries, we start by identifying a variety of campaign scenarios that force commanders might be asked to confront. Effects ladders then can be developed for each scenario, at least to the point where the most challenging decisive moments are identified. Figure 3 shows an example of an effects ladder taken from an overview of effects-based operations developed by the Air Force Research Laboratory [7], which shows how these decisive moments progressively build to a campaign outcome.[6]

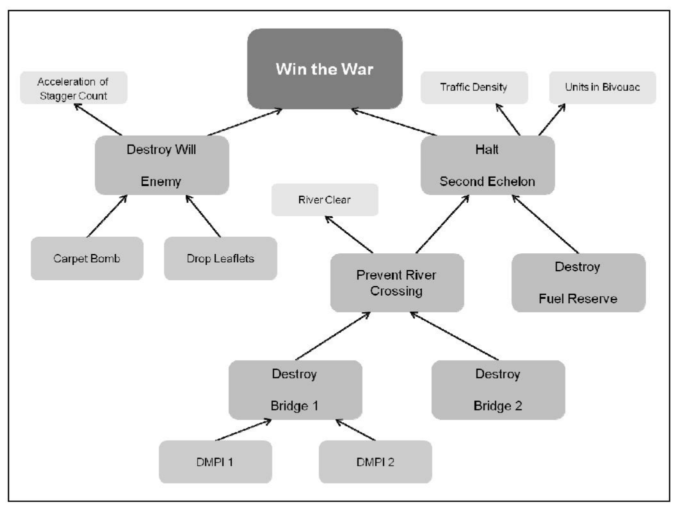


Fig. 5: Effects Ladder

[4] Note the importance here of these two meanings of the word "moment," the one defining a relationship to clock time and the other referring to its subjective import or effect.

[5] The DoD identifies the Universal Joint Task List (UJTL), which defines basic capabilities. In UK terms, these are the Force Elements defined at the lowest level of autonomous performance possible—such as a missile battery or a platoon.

[6] A parallel from the medical profession would be a doctor identifying the variety of patient conditions she might be asked to treat. An effects ladder in each patient's case would describe the decisive moments in the treatment of each patient's condition within the context of that patient's life.

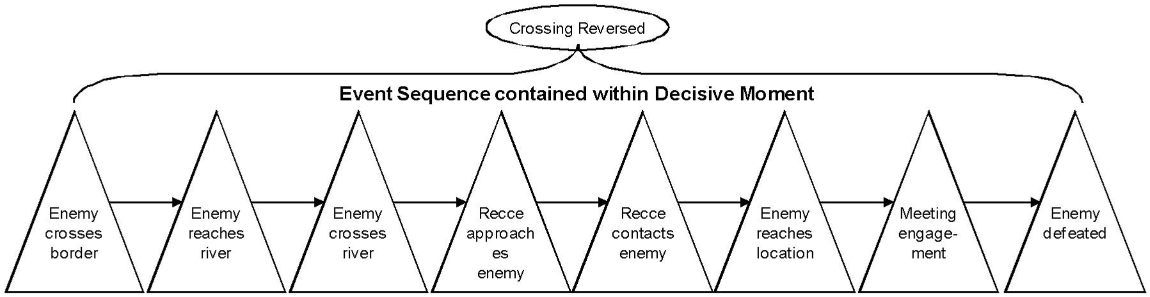
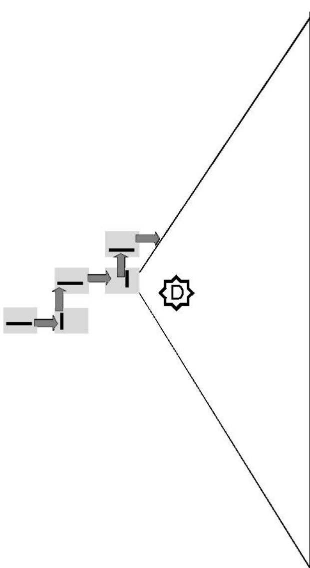


Fig. 6: Sequence of Events contained in Decisive Moment (Note: The British, Canadian, and Australian military use *Recce* as shorthand for reconnaissance.)

Having selected decisive moments that are particularly demanding—for example, "prevent river crossing" in the Figure 5 effects ladder—the next step is to identify the operational capabilities needed. One way to do this is to identify the sequence of events that must happen to satisfy the decisive moment, and then identify the operational capabilities that must be synchronized for each event (Figure 6). These will be defined by the operational commander in a way that partly reflects the constituent capabilities available to him and partly how he is thinking about the nature of the decisive moment. [7]

The Figure 7 Synchronization or Mission matrix is such a description. Each column represents an event in the sequence in Figure 6, defined in terms of the Composite Capabilities (rows) that need to be synchronized to address the Decisive Moment. Implicit in this thinking will be the commander's concept of operations and knowledge of what can be achieved with the capabilities.

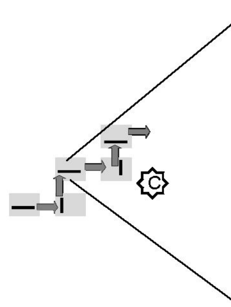


Decisive Moments

Enemy crosses boarder	Enemy reaches river	Enemy crosses river	Recce approaches enemy	Recce comnes into contact with enemy	Enemy reaches meeting engagement location	Meting engagement	Enemy defeated	Enemy follow-on forces advance	Composite Capabilities
X	X	X	X	X	X	X	X		Support Recce
X	X								Identify enemy routes
		X	X	X	X				Report state
X	X	X							Identify crossing
	X	X	X						Continuous observation
X	X	X	X						Detect and Track
		X	X	X	X	X			Cue strike
				X	X	X	X		Bda
				X	X	X			Monitor
			X	X	X	X			Identify tragets
X	X	X							Identify patrols
	X	X	X	X					Support deception
X	X	X	X	X	X	X	X	X	Report movement

Fig. 7: Synchronization (Mission) Matrix

The next step (Figure 8) is to identify the Operational Capabilities needed to generate these Composite Capabilities. In this example, 14 force elements were used (horizontal axis). Each row defines a geometry-of-use (a specific Composite Capability), representing the particular form of interoperation and cooperation required between force elements (specific Operational Capabilities) in order to generate that geometry-of-use (the specific Composite Capability).



Operational Capability

Force element 1	Force element 2	Force element 3	Force element 4	Force element 5	Force element 6	Force element 7	Force element 8	Force element 9	Force element 10	Force element 11	Force element 12	Force element 13	Force element 14	Composite Capabilities
x	x	x			x			x					x	Support Recce
x	x	x	x		x	x		x					x	Identify enemy routes
x	x		x	x		x	x	x						Report state
x	x	x	x	x	x	x	x	x						Identify crossing
x	x	x	x		x	x								Continuous observation
x	x	x	x		x	x						x		Detect and Track
x	x								x	x	x	x		Cue strike
x	x		x	x		x	x		x	x	x	x		Bda
x	x		x	x		x	x		x	x	x	x		Monitor
x	x			x		x		x				x	x	Identify tragets
x	x					x		x				x		Identify patrols
x	x		x			x								Support deception
x	x			x		x	x	x				x	x	Report movement

Fig. 8: Geometries-of-Use Matrix

In this case the events were used to elicit the operational capabilities and corresponding geometries. With experience, however, a force commander finds it easy to directly identify the critical geometries-of-use associated with each decisive moment.[8] The resultant geometry-of-use matrix can then be analyzed as a geometry landscape (see Figure 9) in order to study the variety of geometries that must be supported. In this landscape, geometries are adjacent on the x axis if they share common force elements. Thus a peak indicates that the neighboring geometries are very similar, while a valley indicates that there are important differences. The more jagged the landscape, the greater the variety of force elements supporting the geometries-of-use.[9]

[7] In the health care domain Clinical Practice Guidelines (CPGs) attempt to standardize such ladders.

[8] In the case of our doctor, each decisive moment in the treatment of the patient will contain its own sequence of steps, which in turn will require the orchestration of a number of medical capabilities. Thus in order to stabilize a knee joint sufficiently to bring down its swelling so that it can be operated upon, medication, scanning, orthoses, and physiotherapy must be orchestrated. The variety of patient conditions encountered will determine the variety of geometries-of-use the doctor must be able to draw upon.

[9] One of the difficulties facing an emergency department in a hospital is that this landscape will be considerably more jagged than for a special-

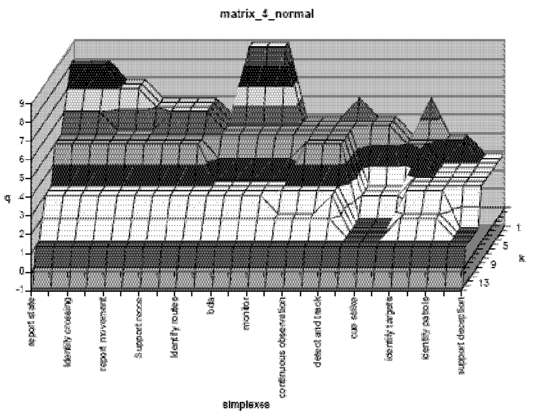


Fig. 9; Geometry-of-Use Landscape

Herein lies one of the key design-time enablers of use-time agility. The SoS infrastructure must be able to support (actually an economic subset of) these geometries-of-use. By analyzing the ability of the underlying infrastructures to support the variety of geometries identified, we may assess the risk that requisite agility is lacking. This interoperability risk analysis looks for gaps in the forms of interoperability needed by each geometry [8].

These scenario-driven cascading matrices are very useful in determining the granularity and compositional needs for software enabled components in complex software intensive systems of systems (SoS). The cascading matrices provide a hybrid model of the organizational, technical, and pragmatic dimensions required to support dynamic orchestration and synchronization of the actors and assets involve in the socio-technical SoS. The technique is naturally scalable, i.e. the constituent pieces scale to the granularity of the focus of interest and knowledge of the participating community of interest. It can be used to reason about the major systems that are required to support a regional healthcare organization or a military capability as well as understanding the appropriate software service mix required to support an electronic performance monitoring dashboard of either.

A key aspect of the analysis technique is its ability to identify types and categories of functionality within the infrastructure needed to support the levels of agility required by the variety of demands made by decisive moments. This in turn facilitates the characterization of the required forms of coupling interface and functional granularity provided by the infrastructure that will more readily accommodate unknown future demands.

6 CONCLUSION

The systematic determination of the variety of geometries-of-use arising from the demands of decisive moments in a systems-of-systems environment provides a process for aligning the pragmatics of demand associated with those decisive moments with the constituent parts of socio-technical systems of systems. The tools and processes that support this systems engineering are directly applicable to the challenges of maximizing agility and identifying interoperability risks, and involve moving beyond the semantics of interoperability in complex software-intensive systems of systems to consider organizational and pragmatic issues. These techniques also provide a reasoning framework for making tradeoff decisions about the costs and benefits of developing and sustaining constituent capabilities in the forms needed to provide the agility required to respond to rapidly changing demand.

Whether we are building the GIG or a hospital's information technology infrastructure, we will need to engineer infrastructures that are agile enough to support the pragmatics of demand if we wish our software to support the expressive range achieved by a symphony orchestra.

7 FUTURE WORK

These approaches to defining the relationship between the pragmatics of demand and the required variety of geometries of use that an infrastructure must be able to support form part of the SoS Navigator Framework being developed by the ISIS group within the SEI.

ACKNOWLEDGEMENTS

We draw upon Maier for Systems of Systems definitions and Alberts and Hayes for agility, "power to the edge," and asymmetric threat foundations. Even more, we rely most heavily upon Boxer and Cohen and their prior efforts in the UK with industry and the Ministry of Defence in the development of these techniques [9] [10].

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