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# Selected Considerations in Systems of Systems − 1

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# Abstract

For many large-scale, systems-intensive organizations, the tempo of operations using software-reliant systems is different from that of the acquisition or development processes for those systems. Organizations use a variety of approaches that attempt to synchronize, for operational use, the integration and fielding of interoperating software-reliant systems. They continue to confront the issue of how fielded software can support the increasing agility needed by a deployed, operational workforce.

This paper describes three concepts that we find useful in explaining the problem and in reasoning about possible solutions: (1) understanding a double challenge related to governance and how an enterprise responds to the demands in its environment, (2) sustaining an operations-driven perspective, even while many of the constraints relate to managing from the central parts of the organizations, and (3) making effective use of stratification, a layered approach to relating key system-of-systems engineering and governance issues.

# 1 Introduction

Many commercial, government, and military organizations are designing, developing, and fielding systems with the expectation that they will be a part of a larger federation of independent systems, commonly termed a *system of systems* [(Miller), (Singh), (Beaudouin-Lafon)]. The U. S. Department of Defense (DoD), for instance, is moving rapidly toward network-centric operations, in which individual weapons systems become related elements in a global web of independently evolving systems that serve multiple purposes. Efforts like the Single Integrated Air Picture (SIAP), which bring together information from multiple services from dozens of individual systems, exemplify this movement. In the finance, manufacturing, healthcare, and service industries, network-based computing is also proliferating.

These systems no longer operate in isolation. Rather, they must interoperate, often in ways that are unplanned, with other systems that may or may not be known until installation or during operations. This situation is reflected within the DoD acquisition community as it confronts the issue of how to continually build or enhance fielded, interoperating software-reliant systems that can support the agility needed by a deployed, operational force engaged in both U.S. and coalition actions.

The struggles that organizations are experiencing with their large-scale, software-reliant systems bring to light the effect a difference in *tempo* among acquisition, development, and operations can have. Increasingly, the *agility* required by the operational or business elements of an *enterprise* to respond to changes in the demands of its customers outpaces the ability of the development and acquisition elements to provide support that enables the needed agility. To provide effective solutions, we recommend shifting from a single-system technical focus to a system-of-systems focus that includes technical and organizational elements. Without focusing on this broader range of elements, individual systems are likely to meet their original intent, but are unlikely to meet the demands of users whose needs are changing as their environment changes.

The premises we describe are responses to three *new realities* emerging from needing to achieve sufficient agility with fielded systems of systems while maintaining effective development and system evolution. These new realities are as follows:

1. The problem space is larger than that defined by the acquisition process and is best described in terms of a *double challenge,* which affects the *governance framework* that the enterprise can use if it is to remain responsive to its demand environment.
2. The larger space needs to be approached in terms of the balance among eight organizational dimensions that capture critical factors associated with providing edge-driven operational capability.
3. An *edge-driven perspective* leads to making a fundamental distinction between hierarchical (focused on "vertical" accountability relationships) and stratified (focused on "horizontal" service relationships) ways of organizing people and tasks.[1]

[1] An edge-driven perspective views the enterprise from the point at which its operational activities interact directly with the needs of the customer, including those that arise within the customer's context.

In this technical note, we first summarize the three new realities and their associated premises (Section 2). Then we analyze each new reality about the problem space and its corresponding premise in more detail (Section 3). This analysis leads to possible implications that organizations facing the new realities might consider (Section 4).

# 2 Overview of the Three Premises

Table 1 introduces three new realities and the system-of-systems (SoS) premise related to each one. These pairs are examined in Section 3.

*Table 1: Relating New Realities about this Problem Space to SoS Premises*

| New Reality | SoS Premise |
|---|---|
| The problem space is larger than that defined by the acquisition process and is best described in terms of a *double challenge* which affects the *governance framework* that the enterprise can use if it is to remain responsive to its demand environment.<br><br>(The double challenge revolves around the tensions that arise in aligning different forms of supply complexity to different forms of response to operational demands within a situation.) | To make the double challenge tractable, we need to analyze the range of both the forms of *supply complexity* and the forms of *relationship to demand* that are relevant. |
| The larger space needs to be approached in terms of the balance among eight organizational dimensions that capture critical factors associated with providing edge-driven operational capability.<br><br>(Edge-driven refers to the parts of an enterprise whose work is focused on responding to the operational needs of customers, and even to their customers' customers.) | To understand how cohesive operational behaviors are generated at the edge, we need to analyze the forms of balance among eight organizational dimensions. |
| An edge-driven perspective leads to a fundamental distinction between *hierarchical* (focused on "vertical" accountability relationships) and *stratified* (focused on "horizontal" service relationships) ways of organizing.<br><br>(How the enterprise organizes itself has implications for how technology and governance support infrastructures can be constructed.) | To align available technologies with the variety of operational contexts in which they will be used, we need to analyze their stratification in relation to the required variety of deployment configurations they must support. |

# 3 Three New Realities and Related SoS Premises

In this section, each new reality is examined and paired with an SoS premise that answers it.

## 3.1 FIRST NEW REALITY: THE PROBLEM SPACE IS BEST DESCRIBED IN TERMS OF A DOUBLE CHALLENGE

Current acquisition efforts focus on producing a definable product at the conclusion of a program for which a program management office is accountable. When fielded, this product, if it is a software system, will form part of a solution to some problem that a user has (or had). Because user needs change at a much faster pace than the tempo of system acquisition, it is very likely that the requirement will have changed, a circumstance that may not be communicated to the acquisition program. Acquisition processes do not deal well with tempos driven by significant and frequent changes to requirements driven by operations in the field

The challenges facing acquisition processes can be approached in terms of two fundamental dimensions: (1) the form of supply complexity for which accountability for performance must be created across one or more enterprises, and (2) the type of complexity generated in response to demand. These two dimensions define a system-of-systems *Problem Space*.

In Figure 1, this Governance Space is depicted as a grid based on those dimensions, in which the top-right corner represents a double challenge. The vertical aspect represents the way the supply complexity affects how accountability can be imposed on the enterprise(s). The horizontal aspect represents the way the relationship to the customer's demand is defined. The blocks in the diagram reflect different combinations of supply complexity and relation to demand.

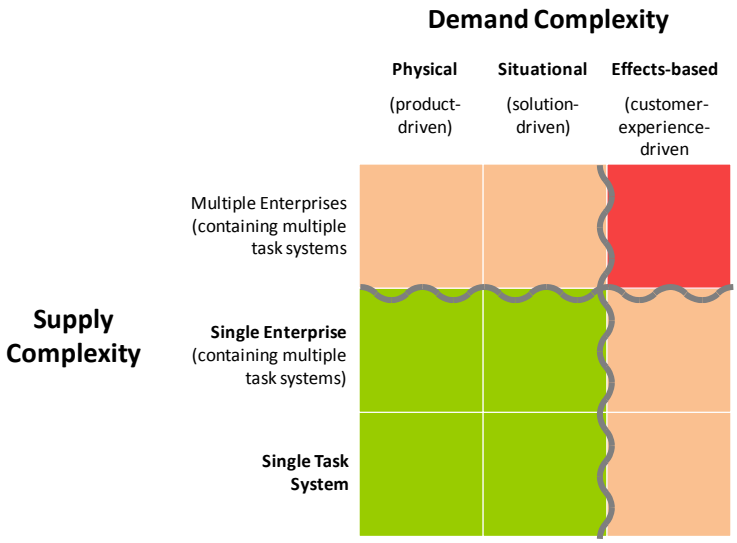


*Figure 1: The Problem Space in which the Double Challenge Occurs*

- Authority in the bottom row is exercised over a single task system (often an individual project); it progresses (vertically in the figure) to authority exercised over a single enterprise

that contains multiple projects. Continuing above the horizontal squiggly line is the challenge in which effective authority has to be negotiated across multiple enterprises.

- The horizontal axis defines the role(s) that the enterprise assumes in relation to customers. The concept of *customers* ultimately includes their operational contexts, which is where their demands arise (Prahalad and Ramaswamy). The understanding of those demands depends on how the supply complexity of the enterprise is defined.[2] In the first column of Figure 1, the role is defined purely in terms of the physical characteristics of the product to be delivered into a *product space*. In the middle column, the role is defined in terms of solutions to be delivered in response to predefined customer problems in a *solution space*. In the last column, the role is to provide solutions that change dynamically with the customer's changing needs within the customer's *experience space*.

  The vertical squiggly line is between the solution-space and the experience-space, because of the shift needed from a view of supply driven by the supplier's view of the customer's requirements to an edge-driven view of supply that is a demand-side view of the customer's ongoing experience. The view focused on customer requirements says in effect "Before I—the supplier—can offer you a solution, you—the customer—must first tell me what your problem is." The edge-driven view implies "I—the supplier—am here to organize and align solutions that will address the ongoing and evolving needs of you—the customer."

  Objectively, the difference when focusing on the customer experience is that the needed solution changes over time in ways driven by the nature of the customer's situation rather than by the nature of the products or solutions that are "in stock." But subjectively, the form of governance framework needed must delegate authority to the edge where the customer's evolving needs can be known. The challenges of working across multiple enterprises are compounded by the need to do so in ways that are responsive to the dynamically evolving (and emergent) needs of customers. This is the essence of the double challenge (Boxer, Morris and Smith).

If we consider the extent to which asymmetric threat[3] and counter-insurgency roles have come to represent the new challenges facing an edge-driven U.S. Army, it is apparent that both the effects the Army is trying to generate and the threats that it is trying to counter (the customers that they are ultimately seeking to "serve") are moving into this top-right space. But the approach to delivering systems against requirements for a specific product under a fully accountable PMO still falls in the bottom-left space of Figure 1.

**SoS Premise 1: To make the double challenge tractable, we need to analyze the range of both the forms of *supply complexity* and the forms of *relationship to demand* that are relevant.**

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[2] The progression along this axis also represents a shift from a 1950's competitive focus purely on the outputs of the enterprise (sold to a wide variety of users) through to the current competitive focus on the needs of the particular customer (Porter).

[3] Cadet First Class Kolodzie (USMA) comments on Army viewpoints on asymmetric threats common in the 1990s (Kolodzie).

## 3.2 SECOND NEW REALITY: DEALING WITH THE PROBLEM SPACE REQUIRES ADDRESSING A SPECTRUM OF EIGHT ORGANIZATIONAL DIMENSIONS REQUIRED FOR EDGE-DRIVEN ENTERPRISES

Eight organizational dimensions, adapted from the DOTMLPF[4] acronym used by the DoD (Joint Publication 1-02), are shown in Figure 2 to reflect the double challenge described in Section 3.1. The dimensions are the criteria for evaluating and understanding the problem space defined by the enterprise's double challenge.

The dimensions driven from the *center,* shown above the diagonal line in Figure 2, are derived from the central sources of the authority (driven by the forms of supply complexity in Figure 1):

1. *Doctrine & operational concepts*: the principles and operational methods underlying the approach to generating ultimate effects in a situation
2. *Facilities & infrastructure:* the facilities and infrastructure that are the context within which the enterprise performs its work
3. *Leadership & education:* the ability to lead the enterprise creatively and effectively within the context of its chosen business or mission domain
4. *Materiel & technology:* the tools and technologies that the enterprise needs to be effective within its chosen business or mission domain

The dimensions driven from the *edge,* shown below the diagonal line in Figure 2, are those that the governance framework delegates to be shaped by the particular situations at the edge (the customer experience-based column as illustrated in Figure 1).

1. *Edge organization*$_v$*:* the way of organizing$_v$ needed to orchestrate and synchronize the capabilities needed to meet the demands arising from a particular customer situation
2. *Collective training for edge personnel:* the people that are needed by the way of organizing$_v$ at the edge, provided with the appropriate know-how and abilities to work together collaboratively
3. *Situational understanding:* the way data is able to be fused and interpreted to provide a composite picture of what is going on in any given particular situation
4. *Personnel & culture*: the socialization, background, and mutual knowledge that people need to be able to trust each other and to work together at the edge

[4] In the DoD, the acronym DOTMLPF captures the issues to be considered when defining an operational capability: doctrine, organization, training, materiel, leadership and education, personnel, and facilities.

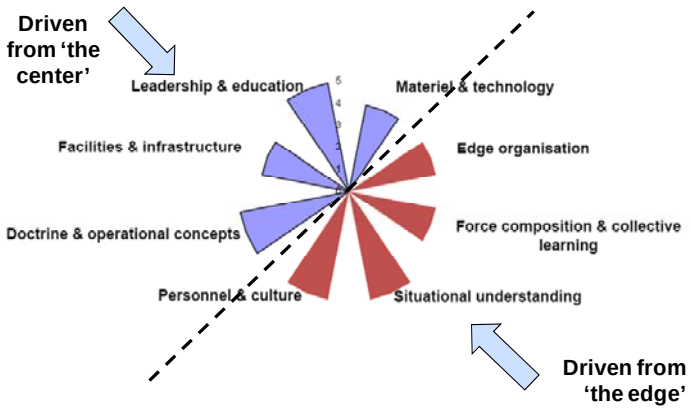


*Figure 2: The Eight Organizational Dimensions Requiring Alignment*

The extent to which all eight dimensions align with one another through collaborative processes will determine the agility of an enterprise's operational behaviors at the edge. Typically, the investment of time and money by the enterprise goes into the first four dimensions (the center-driven dimensions), leaving the second four to informal processes. The challenge is to give balanced attention to all eight, with the edge-driven dimensions becoming increasingly important as the environment demands increasing levels of agility.

**SoS Premise 2: To understand how cohesive operational behaviors are generated at the edge, we need to analyze the forms of balance among eight organizational dimensions.**

## 3.3 THIRD NEW REALITY: SOLVING THE PROBLEM SPACE REQUIRES AN ALIGNMENT OF THE SUPPLY SIDE AND DEMAND SIDE

To effectively deal with the alignment challenges related to center-driven and edge-driven organizational issues (Section 3.2) that result from the double challenge (Section 3.1), we need an analytical framework that describes what is necessary to align supplied equipment, people, and materials on the supply side to generate the desired effects on a particular customer's operational space on the demand side. Stratification, the layering of related elements within a larger context, provides such an analytical framework. Using stratified layers, we can analyze the kinds of engineering, governance, and processes that are needed to generate alignment in ways that are appropriately dynamic and agile to a particular situation.

### 3.3.1 Stratification

Figure 3 shows a generalized example of how governance and engineering processes need to be aligned to satisfy the needs of a military campaign, using terminology common to that context. The bottom three (supply side) layers of Figure 3 show the available technological capabilities, while the top three (demand side) layers show the way these technological capabilities are brought to bear on the environment in which demands must be satisfied. The left hand of the diagram differentiates the typical sources of constraints for the different layers of the stratification. For the bottom three layers, the constraints come from the choices made in how the technological capabilities are engineered. For the top three layers, the constraints come from the environment itself and

the choices that have to be made to respond to the particular demands that emerge from it (the pragmatics of a situation).

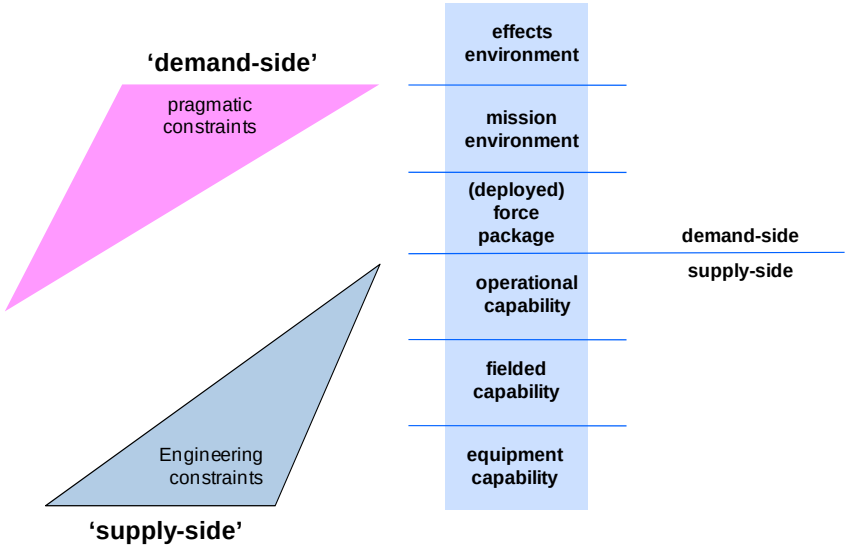


Figure 3: Supply-Side versus Demand-Side Showing Stratification

Six layers can be distinguished in this stratification, each one supporting the layer above it. *Support* here means that the services in any given layer are embedded in the one above it, making these a set of nested contexts.

- Layer 1 is *equipment capability*, corresponding to the systems provided by suppliers in response to a set of pre-defined requirements. Government Program Management Offices focus on this layer, because they must make sure that the supplier delivers to requirements, to budget, and on schedule.
- Layer 2, *fielded equipment*, is the equipment from layer 1 together with all the surrounding services that enable it to be used in the field. In this layer, a given system is tested by its users to establish whether or not it meets its acceptance criteria.[5]
- Layer 3 is an *operational capability* that uses fielded equipment, but surrounds it with the skills and processes needed to make it useful and usable (e.g., the typical DOTMLPF-enhanced equipment planned for by the Army). This layer, therefore, refers to an operational unit that is ready to use the system as part of the way it delivers operational capability.

In Figure 3, these supply-side layers are represented by an inverted pyramid that builds the operational capability on the foundations of the equipment capability in a way that is constrained by the engineering of that equipment. We use the term '*over-determining*' to refer to the ways that engineering often dictates how a system can be used. From the point of view of the users of the operational capability at layer 3, these engineering constraints are over-determining if they restrict the choices open to the user for how the capability may be used. Thus, for example, the way an Osp-

[5] Whole Product thinking addresses this layer 2 (Wikimedia).

rey aircraft must commit to landing, because of how its propellers rotate, places constraints on the kinds of operational environments in which it can be deployed.[6]

The demand-side layers define the actual uses of operational capabilities, along the lines of engineering the operations environment, not just the supplied product:

- Layer 4 represents a *deployed force* made up of operational capabilities that must be able to work together in ways that can support the missions and business objectives expected of it. In this layer, individual operational capabilities are orchestrated with other capabilities to create mission capabilities. The deployed force must be prepared for the variety of mission capabilities that it will support. An example of this is a joint services team that includes land, sea, and air assets focused on eliminating a particular threat. In the exercise of that mission, the combination and use of the land, sea, and air assets depends on the situation that the team finds when it arrives in theatre. And those combinations will involve a variety of mission capabilities depending on how long and how far the team has to go to succeed in elimination of the assigned threat.
- Layer 5 is the *mission environment* in which the deployed force will operate. In the Army, the nature of this mission environment depends on the campaign plan that the force command has in mind. Any given mission in this environment will involve the synchronization of mission capabilities with the intention of generating particular forms of effect. To continue with the above example, the mission environment that the joint team supports includes both military and non-military tactics. Synchronizing the non-military actions (enlisting local resident support in identifying the location of the threat, for example) with the military actions is important if ongoing support from the local residents is one of the overall mission goals.
- Finally, layer 6 is the *effects environment* in which that variety of missions is to be used to generate particular effects in response to the threats or demands being presented by that environment. This layer is often described by operational scenarios. In the Osprey helicopter example, the effects environment would be represented by the nature of the mission and the variety of threats that could be encountered in achieving that mission. If we know that the Osprey is unsuitable (based on its operational capability constraints) for certain types of landing situations, then understanding the effects environment will be important to assuring that the proposed landing area will not violate those constraints. Thus in the preceding joint team mission example, if the physical effects environment includes urban areas that are full of rubble due to bombings, the Osprey is not a good candidate for use in that mission unless the team has a way of clearing a suitable area for landing.

UAVs (Unmanned Aerial Vehicles) provide another example of the criticality of alignment between supply side and demand side. UAVs originally had very limited operational capabilities and so were only used for a relatively simple set of missions. As sensor, communication, and remote control technologies have improved over time, UAVs can physically operate in a much more demanding and complex set of mission environments. However, it is tempting for those controlling budgets for UAV improvements to focus only on the current set of mission needs without anticipating feasible possibilities for future missions.

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[6] The reference here is to approaching unprepared landing zones (FAS Military Analysis Network).

Figure 3's stratification can help engineers understand the need for retaining flexibility in some of the UAVs' sensor and remote control systems, so that the widest variety of mission effects can be achieved with UAVs. For example, the sensor outputs of a UAV might be orchestrated in layer 4 with outputs from signals intelligence reports, to support a mission capability in layer 5, in order to pinpoint a new kind of target identified.

Layer 3 is also affected because the orchestration process may need to reach back to the operational capabilities and customize them so that they can participate in their orchestration with other operational capabilities (e.g., the sensors on the UAV might need to be reconfigured for their outputs to be usable in this orchestration). This ability for alignment is of fundamental importance: *if the operational capabilities in layer 3 over-constrain the ways in which they can be used in layers 4 and 5 (because of how they were engineered in layer 1 and fielded in layer 2), then the mission constraints cannot be satisfied.*

### 3.3.2 Managing the Alignment of the Supply Side and the Demand Side

Figure 4 shows a more generic stratification and the way this version of the stratification aligns to the military-specific stratification in Figure 3. The right side contains the stratification we used in Figure 3. The left side provides a more generic stratification that can be used as a starting point when dealing with an unknown set of systems of systems.

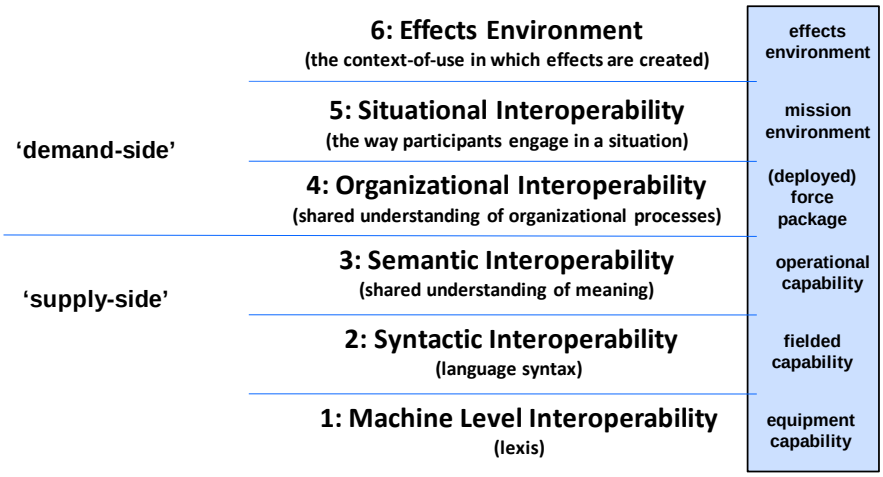


*Figure 4: A Generic Stratification for Interoperability*

To align current operational needs with systems coming online—in a manner that takes account of the deployment and other constraints—government acquisition programs could try to balance the program focus of systems at layers 1 and 2 with the pragmatic constraints introduced by layers 3 to 5. The balancing of those supply-side and demand-side layers would be done within the context of layer 6. The example of a UAV can illustrate this balance: the engineering of a particular UAV model would be aligned with the variations in deployment context which UAVs of that model need to address now and in the future within the context of the variety of threat environment in which missions that involve UAVs occur.

The key task is to define the content of the different layers and the way each layer is organized$_v$ to align the layers below and above it. This task requires analysis of

- which configurations of operational capabilities represented in a deployed force are critical to supporting which mission environments
- which functionality and threads are critical to supporting which configurations

We must make the problem space tractable by being able to identify, align, and prioritize the testing and deployment process from the perspective of particular mission environments. We need to ask where resources are currently being wasted and where the greatest impact can be created on mission capabilities. Structural modeling techniques are needed to distinguish critical elements of both supply-side and demand-side constructs and to represent the operational concepts inherent in a particular stratification (Anderson, Boxer and Brownsword).

**SoS Premise 3: To align available technologies with the variety of operational contexts in which they will be used, we need to analyze their stratification in relation to the required variety of deployment configurations they must support.**

# 4 Implications

Clearly, the tempo of operations is different from that of acquisition or procurement, for the Army and other systems-intensive organizations that acquire, build, deploy, and maintain large-scale, software- reliant systems. How, then, are fielded software systems to be defined in such a way that they support the agility needed by operations?

We suggest a number of ways organizations (military or otherwise) might approach this question:

- Identify strategies for better investment decisions within the acquisition/development context based on a bigger (stratified) picture.
- Propose changes to the synchronization and integration of software. The changes would be based on methods for improving the prediction of and planning for the required varieties of deployment context that need to be supported and should take into account the impact of existing systems on the introduction of new ones.
- Identify ways to test and decompose (1) missions or business operations, based on the critical variety of demands for effects, and (2) changes to testing and certifying interoperability and net-readiness, based on the corresponding critical deployment configuration.

The expense alone of building software-reliant systems demands that we get the most effective use from them. But to get effective use from our systems, we must understand what "effective use" is in the variety of human and machine usage contexts into which these systems can be feasibly deployed. This technical note proposes new ways to approach this challenging aspect of systems development by achieving the needed balance between our traditional supply-centered focus and the user, demand-centered focus that is increasingly needed.

# Glossary of Terms

**agility** - the ability of the operational or business elements of an enterprise to respond to changes in the demands of its customers. 9

**demand-side layers** – the top three layers of a stratification. 15

**double challenge** - The challenge of being both *edge-driven* and collaborating with multiple *enterprises* 9, 11

**edge-driven perspective** – an edge-driven perspective views the enterprise from the point at which its operational activities interact directly with the needs of the customer that arise within the customer's context. 9

**enterprise** – a form of organization defined by its having a single overall focus of effective accountability for its performance. 9

**experience space** - a space in which customers' choices are expressed in terms of their own experience, in which they anticipate the experience of effects. These are the through-time experiences of effects that the customer has as recipient of the suppliers' services within their own context-of-use. 13

**governance framework** - the form of framework within which accountability for performance is established across one or more enterprises in relation to demand. 9

**hierarchical relationships** – 'vertical' relationships focused on accountability. 11

**new realities** - the new realities in Table 1 that give rise to the three premises needed to make the system-of-systems challenges tractable, namely the *double challenge*, the *DOTMLPFS wheel*, and *stratification.* 9

**over-determining** – the ways that engineering dictates how a system can be used.' 16

**problem space –** the problem space defined by the relationship between supply complexity and the type of complexity generated in response to demand. 12

**product space** - a space in which customer's choices are expressed in terms of the qualities of one product versus another independently of their context-of-use. 13

**solution space** - a space in which customers' choices are expressed in terms of the different solutions offered to customers' stated problems. 13

SoS Premise 1 - **To make the double challenge tractable, we need to analyze the range of both the forms of *supply complexity* and the forms of *relationship to demand* that are relevant.** 13

SoS Premise 2 - **to understand how cohesive operational behaviors are generated at the edge, an analysis has to be made of the forms of balance among eight organizational dimensions.** 15

SoS Premise 3 - **To align available technologies with the variety of operational contexts in which they will be used, an analysis has to be made of their stratification in relation to the required variety of deployment configurations they must support.** 19

**stratified relationships** – 'horizontal' relationships focused on the services delivered at the edge of the enterprise. 11

**supply-side layers** – the bottom three layers of a stratification. 15

**tempo** – the rate at which an event occurs within a given timeframe. 9

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13 ABSTRACT (MAXIMUM 200 WORDS)

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This paper describes three concepts that we find useful in explaining the problem and in reasoning about possible solutions: (1) understanding a double challenge related to governance and how an enterprise responds to the demands in its environment, (2) sustaining an operations-driven perspective, even while many of the constraints relate to managing from the central parts of the organizations, and (3) making effective use of stratification, a layered approach to relating key system-of-systems engineering and governance issues.

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