Software Engineering Institute

Conditions for Achieving Network-Centric Operations in Systems of Systems

David A. Fisher
B. Craig Meyers
Pat Place

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SEI Administrative Agent
ESC/XPK
5 Eglin Street
Hanscom AFB, MA 01731-2100

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Abstract

The advantages of systems of systems—such as the ability to adapt to unanticipated and unforeseen situations, eliminate single points of failure, and remain continuously operational while being dynamically updated—guarantee their increasing importance to military and commercial environments. The advent of network-centric systems has served only to accelerate the already prevalent move toward systems of systems.

At the same time, network-centric systems and systems of systems are proving difficult to acquire, develop, test, and operate. Many of them are abandoned before they can be fielded, and fielded systems often fail to satisfy their objectives—demonstrating cost and schedule overruns in their development and sometimes catastrophic failures in operation.

The increasing disparity between the normative (but nonfactual) assumptions that underlie current practices and tools used in the acquisition, development, evolution, and operation of systems and the realities of actual systems of systems contributes to those problems. Effective practices and tools for the acquisition, development, and operation of systems of systems have not yet been developed. Suggesting a context in which those practices and tools can be developed, this technical note proposes necessary conditions—statements of what the desired future state should be—in six areas that influence the effectiveness of network-centric systems and systems of systems: (1) social and cultural environment, (2) legal and regulatory framework, (3) management practices, (4) governance procedures, (5) engineering practices, and (6) technology base.

1 Introduction and Overview

A primary focus of the Carnegie Mellon® Software Engineering Institute (SEI) Integration of Software-Intensive Systems (ISIS) Initiative is to improve the state of the practice in the acquisition, development, and operation of network-centric systems of systems. This technical note is one in a series of papers leading to a vision and research agenda for software engineering in system of systems. While some earlier papers focused on the current state of the practice,[1] the intent here is to identify some of the conditions that must prevail to achieve effective acquisition, development, and use of systems of systems.[2] The difference between current practice and the necessary conditions provides a foundation for a vision and for building a research agenda to fulfill that vision.

The policies and practices that dominate all aspects of the life cycle of traditional systems have evolved from a number of simplifying assumptions. Although never regarded as accurate, these normative assumptions have been pervasively adopted and have often proven effective in the acquisition, development, and use of systems. The normative assumptions include clearly defined system boundaries, the ability to observe all details within the system, effective centralized control, hierarchical management structure, fixed requirements, a common vocabulary among participants, resource elasticity, single administrative domain, the absence of emergent effects, and small numbers of only linear variables to be managed.[3] Informally, a monolithic system is any system whose characteristics and context closely match these assumptions.

The advent of network-centric systems has intensified and accelerated the already prevalent move toward systems of systems. The disparity between the often unstated assumptions that underlie current acquisition, development, evolution, and operation of systems and the realities of actual systems of systems leads to more and more failures and to reduced effectiveness of systems as they become increasingly network centric (see Figure 1).

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1 Earlier papers characterize the state of the practice from a variety of perspectives [Meyers 2006a, Smith 2005, Carney 2005a, Carney 2005b, Carney 2005c, Carney 2005d, Lewis 2004b, Ellison 1997]. Some related ideas are discussed in other ISIS reports [Brownsword 2006, Smith 2006, Meyers 2005, Brownsword 2004, Lewis 2004a, Lewis 2004c, Morris 2004, Christie 2002, Meyers 2001].

2 Many of the characteristics of network-centric systems [Alberts 2003, Alberts 1999] and of systems of systems [Fisher 2006, Moffat 2003, Fisher 1999, Lipson 1999] are discussed in this report as well.

3 Some have observed that commercial off-the-shelf (COTS) products also fail several of these assumptions and thus to a limited extent impose problems similar to network-centric systems.

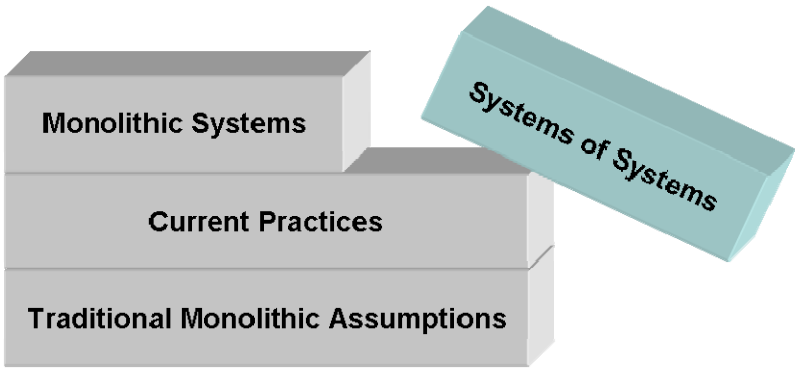

Figure 1: Current Simplifying Assumptions Support Only Monolithic Systems

Systems of systems—with independent development and independent management of their constituent[4] parts, continuous evolution of operational needs, often-undesirable emergent behavior, necessity of interoperation with both unanticipated and legacy systems, and the need for adaptation to unforeseen situations—demonstrate properties that are in opposition to the assumptions of traditional monolithic systems.[5] Systems of systems are unbounded in their acquisition, development, and use. They are unbounded in that regardless of where one draws the boundary, behavior and success inside the system will depend on actions and conditions outside the boundary. A combination of complex structure of dependencies, multiple administrative domains, the presence of proprietary commercial off-the-shelf (COTS) components, interoperation with legacy systems, and other uncertainties guarantees that no one is able to observe all aspects of a system of systems. Centralized control cannot be effective among parallel administrative domains or in contexts where the activity is invisible to the controller.

Pretenses of centralized control aside, distributed control is inherent in systems of systems. Hierarchical structures impose single points of failure for systems as a whole and thus often can be tolerated for noncritical components, but they should be unacceptable for systems of systems as a whole. Real operational needs continuously evolve with change cycles much shorter than those of acquisition and development. Systems of systems must be tested without full knowledge of how they will be used or with which systems they must interoperate. Misinterpretations are inherent in any communication and especially in systems of systems where informal communication can be of critical importance.

Resource limitations (dollars, schedule, or otherwise) impose real constraints on systems of systems that often are mitigated through prioritizing and ultimately shedding some capabilities or mission objectives. Resource limitations are aggravated in systems of systems when priorities differ among constituents. Systems of systems must cross administrative boundaries, and attempts to eliminate such boundaries only aggregate problems by adding additional constraints.

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[4] We use the term *constituent* to reference any automated, mechanized, or human element that can act autonomously within a system of systems.

[5] Our discussion of system-of-systems characteristics draws on work done by Mark Maier [Maier 96].

Emergent behavior is inherent in systems of systems. However, only if emergent behavior is recognized and influenced can its unanticipated negative effects be mitigated and positive effects be exploited. Systems of systems involve large numbers of nonlinear variables—a complexity that cannot be understood and managed through ad hoc manual process methods alone; automated tools, especially for modeling and simulation, and more formalized approaches are needed.

Many advantages that derive from network centricity and systems of systems are unachievable with traditional systems:

- Independence of management and operation of constituent parts facilitates adaptability to unanticipated and unforeseen situations.[6]
- Distributed control means that constituents act autonomously and in ways that reflect changing circumstances of the mission and contribute to the continuing success of the mission. (Although COTS products act independently, their actions are seldom influenced by the evolving needs of a particular mission and thus are potentially single points of failure for the mission as a whole.[7])
- Because constituents of a system of systems can dynamically adapt to changes in their environments, it is not necessary that constituents evolve in lockstep or that all changes be globally coordinated.
- Systems of systems are able to exploit the increased communications bandwidth to provide large quantities of information where and when needed.
- Increased interconnectivity enables cooperative operations with more timely and reliable information.
- Systems of systems can remain continuously operational while being dynamically updated. Like the proverbial ax that has had both its head and handle replaced at various times, a system of systems should be able to operate indefinitely without interruption while undergoing incremental change that eventually replaces all of its functionality and all of its constituent technology.
- To be survivable in a formal sense, systems of systems should be constructed not only to be resistant to single points of failure but also to any number of failures that is less than proportional to the number of constituents [Fisher 1999].

The advantages of systems of systems guarantee their increasing importance to military and commercial systems. At the same time, network-centric systems and systems of systems are proving difficult to acquire, develop, test, and operate. Many systems of systems are abandoned before

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[6] Independence and distributed control can eliminate unnecessary constraints and enable loose coupling that is essential to flexibility and adaptability. As a result, they allow systems to dynamically evolve and adapt in unforeseen situations. At the same time, they conflict with the tight coupling essential to monolithic systems.

[7] One example is the Navy ship that went dead in the water because of a divide-by-zero problem with a COTS product [Lutz 2000].

they can be placed into operation; when they are put into use, they often fail to satisfy their objectives and sometimes demonstrate catastrophic failures.

The problem is not that systems of systems are necessarily more difficult to acquire, develop, test, or operate; rather, effective practices and tools for systems of systems have not yet been developed (see Figure 2). More importantly, whatever their details, those new or improved practices and tools will likely be in conflict with current system acquisition and development practices that are built on assumptions that are no longer valid. This problem exists not only for modern network-centric systems of systems but also for the social systems that acquire, develop, evolve, and operate them.

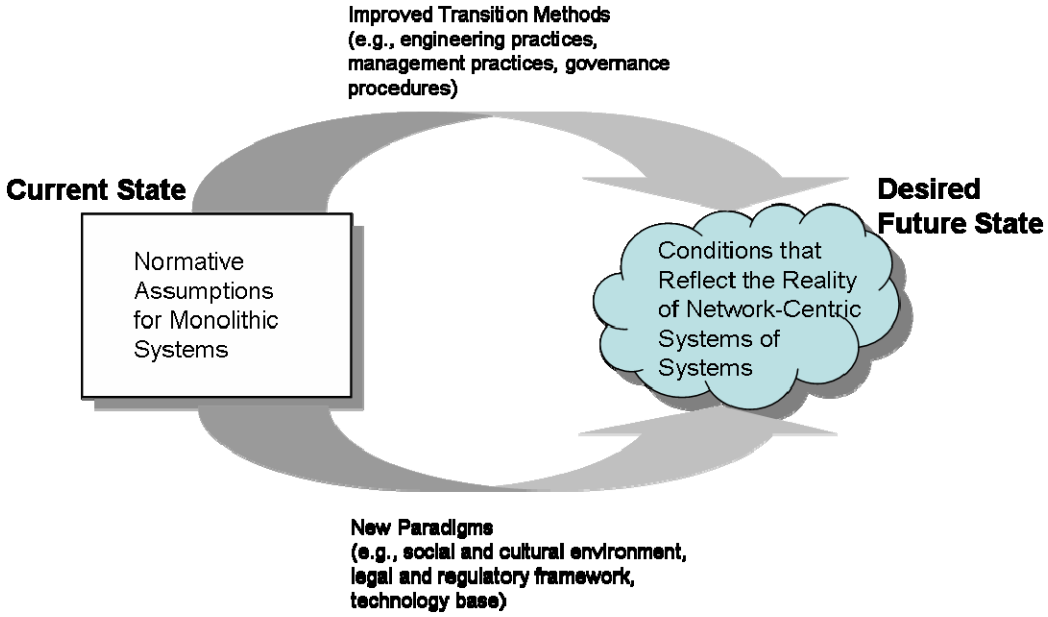

Figure 2: New Practices and Tools are Needed to Realize the Vision for Network-Centric Systems of Systems

The effectiveness of systems of systems for acquisition, development, or operations is influenced by not only the structure and functionality of their software and mechanical and electronic components but also their social and cultural environment, legal and regulatory framework, engineering practices, and governance procedures. Systems of systems can be analyzed on many dimensions, and we can set boundaries between dimensions at many places. The need for a new business model that illustrates how developers or contractors can be profitable in a system-of-systems context, for example, is important but beyond the scope of this report. The sections in this technical note describe necessary conditions to which the following areas must evolve:

- social and cultural environment (Section 2)
- legal and regulatory framework (Section 3)
- management practices (Section 4)
- governance procedures (Section 5)

- engineering practices (Section 6)
- technology base (Section 7)

Distinctions between network-centric systems and systems of systems are unimportant in this report. *Network-centric* is generally used to refer to systems or activities that are enabled by and built upon large-scale communications networks. Thus, most modern military systems of systems are network-centric systems, and military operations are often network-centric operations. The term *systems of systems* refers to those systems that involve multiple independent decision makers, display emergent behavior, necessitate distributed control, or are too complex to be fully visible to any one entity. Thus most modern military systems, including network-centric systems, are systems of systems.

For our purposes, a system of systems is a system for which the normative assumptions of the monolithic system deviate sufficiently from the reality of the system that they are likely to lead to failures in acquisition, development, testing, or operations. In contrast, monolithic systems, although never satisfying these assumptions in the limit, come sufficiently close in most instances that the differences can be ignored.

2 Social and Cultural Environment

Necessary Condition

The social and cultural environment in which systems of systems are acquired, developed, used, and evolved motivates collaborative behavior critical to achieving operational effectiveness.

Rationale/Basis for this Necessary Condition

Success in the acquisition, development, evolution, and operation of any system depends largely on the social and cultural environment in which those activities are carried out. This condition is especially true in systems of systems where progress cannot be effectively dictated or assessed by conventional means; where operational needs change continuously, requiring system configuration and functionality to adapt rapidly in often unforeseen ways; or where critical system components are beyond the control of any one organization.

Discussion

The social and cultural environment of an organization, project, or system emerges from the local actions and neighbor interactions of all its participants and largely determines how individuals and organizations behave.

The social and cultural environment may differ among acquisition, development, and operational organizations. It also may differ among organizations participating in any one of these activities. To the extent that aspects of the social and cultural environment differ—or are in conflict with each other—on critical issues, the acquisition, development, or operation of a system may fail to satisfy its objectives. Divergence among constituencies and organizations involved in a system of systems is more likely where there is a greater number of them and each of them is less specialized.

The social and cultural environment for a network-centric system must be supportive of the inherent properties of systems of systems—and therefore in conflict with many of the normative assumptions that underlie the social and cultural environments appropriate for conventional monolithic systems. For example, in a traditional stovepiped development of a monolithic system, the ultimate measure of success is often considered to be operational effectiveness. Even though nobody believes that contractually established requirements will represent real needs at the end of the development process, systems are not designed to facilitate evolving requirements, requirements are rarely kept current with evolving needs, and contractors are rewarded for satisfying requirements rather than evolving needs. In a system of systems, end-user needs are continuously changing and operational effectiveness can be achieved only through continuous validation from interaction with the operational community. Systems of systems must be developed in a social and cultural environment in which operational effectiveness is accepted as a critical measure of success and the dynamic character of the needs of operational effectiveness is recognized.

More broadly, the social and cultural environment must incorporate an understanding of the need for systems that are flexible and locally adaptable to unforeseen situations. Likewise, it must strive not for maximizing satisfaction of current requirements but for continuous long-term satisfaction of operational effectiveness. The autonomy of constituents and distributed control in systems of systems require open communication and cooperation and a social and cultural environment characterized by a high degree of trust.

The current environment of acquisition and development—as defined by requirements, regulation, policy, contracts, and tradition—is founded on assumptions, shown in Table 1, that although known to be inaccurate prevail nevertheless. These assumptions suffer not only from their inaccuracy but also from a social and cultural environment that counterproductively strives to make them true.

Table 1: Inaccurate Assumptions Underlying Current Environment

Prevailing (But Inaccurate) Assumptions
Operational needs can be known prior to the start of acquisition and development and seldom change thereafter.
Requirements reflect real user needs.
Someone or some group is in charge that has visibility into all aspects of the development and can exercise control over any part of the development process when necessary.
Stakeholders understand the objectives and work toward the same ends.
Adequate money and personnel are available to complete the effort.
Schedules will be met.
Success in all individual components ensures success of the system as a whole.

None of these assumptions is valid in general. Failure to recognize resource limitations, schedule conflicts, and other inconsistencies can be problematic in any system. But for systems of systems, distributed control and independent decision making increase the likelihood of such problems. Furthermore, taking local actions within individual stovepipes to alleviate resource limitations, such as shedding functionality, exacerbates problems. The failure of any one component to support a capability in this monolithic systems approach can eliminate that capability for the system as a whole. Tradeoffs among competing resources must be resolved through consensus on consistent system-wide prioritization of capabilities, not through local optimization or expedience within each constituency.

Actions that can encourage a culture supportive to systems of systems include

- emphasizing the critical importance of operational effectiveness
- educating participants to the distinctive characteristics of systems of systems
- communicating the importance of interoperability to the mission
- creating situations in which all participants have a stake in the success of the system of systems
- establishing cooperative means to build consensus and shared vision among the stakeholders

- establishing a culture that looks for and reacts to changing needs

A sense of belonging, shared ownership in the outcome, elimination of unfunded mandates, prioritization of objectives, elimination of stovepipe development and operations, and active ongoing participation of operational organizations in tradeoffs also can help.

Especially powerful in determining the effectiveness of the acquisition, development, or operation of systems of systems are the reward systems as perceived by participating organizations and individuals. Local reward systems that conflict with global objectives undermine the success of the system of systems as a whole. When local reward systems conflict with one another, it is often an indication that some of them are poorly aligned with global objectives. Reward systems—whether individual, contractual, or organizational—are beneficial only when they are consistent with evolving operational objectives. Rewards need not be monetary. Recognition, budget allocation or relief, advantage toward participation in future projects, and a sense of accomplishment can all be part of an effective reward system.

An effective social and cultural environment for acquisition, development, and operation of network-centric systems must be composed of individuals and organizations that

- have internalized the distinguishing characteristics and implications of system of systems
- can interpret those implications in the context of the current system
- are supported in focusing on operational effectiveness by an appropriate local reward structure
- view success of the enterprise as their individual responsibility
- have sufficient current information to know whether actions are beneficial

Systems of systems offer the potential for flexibility and adaptability to unanticipated situations that is impossible for monolithic systems. Benefits, however, accrue only through recognizing, understanding, and exploiting system-of-systems characteristics. The social and cultural environment must incorporate an understanding of system-of-systems characteristics. But it is not enough to know that independent action, unboundedness, and emergent behavior are inherent or that tight coupling—through requirements for unneeded functionality, burdensome bureaucracy, exaggerated promises or demands, or copious meetings with little value from an individual perspective—will undermine success. Participants must also understand how to exploit that knowledge to advantage and achieve desired outcomes with loosely coupled methods. Through the increased autonomy of individual participants, loose coupling can offer many advantages in quality, productivity, and cost over tightly managed hierarchical structures—but only in a social and cultural environment of shared objectives and strategy.

Cooperation, collaboration, and compromise also require a willingness to suffer suboptimal local solutions for the sake of global optimality. Global refers to both time and space; what is most efficient based on current and locally available information might lead to inefficiencies when later or more comprehensive information becomes available. Furthermore, circumstances are continuously evolving, so that an optimal solution today can be quite inefficient tomorrow. Thus, a sys-

tem-of-systems solution should involve continuous feedback among constituents and local adaptability to new conditions as they become known, leading to systems that are rarely locally optimal but always tending toward global optimality through dynamic adaptability [Fisher 2006].

The social and cultural environment is a cumulative emergent effect implicitly understood by the constituents that emanates from their engineering practices, governance procedures, and legal and regulatory framework—as well as from the technology base, hardware and software infrastructure, and a variety of other influences. At the same time, the social and cultural environment provides the context in which those practices, procedures, and framework must operate. A conflicting or nonsupportive social and cultural environment will make it difficult to achieve expected results.

A new social and cultural environment characterized by trust, cooperation, and shared understanding of evolving operational needs is needed. Establishing an effective social and cultural environment will require goals such as those in Table 2.

Table 2: Goals for Social and Cultural Environment that Supports Network-Centric Systems and Systems of Systems

Recommended Goals
Clearly identify what environmental characteristics are needed.
Remove constraints that are in conflict with those needs.
Eliminate coupling that may preclude effective solutions.
Enable a broad spectrum of experimental approaches from which an effective social and cultural environment can emerge.
Revise reward systems to support evolving objectives.
Develop methods that minimize communication while ensuring that essential information is available when and where needed.
Establish conditions that encourage trustworthy behavior and marginalize the influence of untrustworthy participants.

Although many of these expectations and recommendations are not fully achievable today, they provide goals that are surmountable in the long run. In addition, each increment of progress toward those goals reduces risk and increases the likelihood of success in systems of systems. In the short term, the focus should be on eliminating those aspects of the current social and cultural environment that serve as barriers to achieving necessary reforms in other areas.

3 Legal and Regulatory Framework

Necessary Condition

There exists a legal and regulatory framework to support the acquisition of systems of systems.

Rationale/Basis for this Necessary Condition

The following dichotomy exists within the U. S. Department of Defense (DoD) regarding the network-centric perspective: The operational community desires integrated capabilities to meet a mission, but the acquisition community focuses on delivering a system-oriented solution. Network-centric behavior must occur in more than the operational community.

The ability to acquire systems that are expected to operate efficiently in a network-centric context is fundamental. The acquisition process is governed by many laws, regulations, and policies—all of which are reflected in management practices. The current acquisition environment focuses on a particular system, often at the neglect of the larger perspective.[8] There is also a perception, widespread in the defense community, that the laws and regulations governing acquisition must be revised to support network-centric principles.

Discussion

Our use of the term *legal and regulatory framework* includes laws and the many artifacts derived from statutes, such as regulations, policies, and directives. The acquisition community executes management practices in the context of the existing legal and regulatory framework. Awareness of the need for change in those management practices is not new. For instance, in 2001 then Secretary of Defense Rumsfeld reported, "Despite some 128 acquisition reform studies, DoD has an acquisition system that since 1975 has doubled the time it takes to produce a weapon system—while the pace for new generations of technology has shortened from years to 18 months" [Rumsfeld 2002].

Those studies assumed the acquisition of a single *system*, the focus of existing laws. For example, 10 USC section 2431 (Title 10) states

> *(a) The Secretary of Defense shall submit to Congress each calendar year . . . budget justification documents regarding development and procurement schedules for each weapon system for which fund authorization is required. . . . The documents shall include data on operational testing and evaluation* ***for each weapon system*** *. . .*

[8] Alberts and associates write as follows: "Individual services and agencies currently acquire material and systems one by one. This approach needs to change" [Alberts 1999, p. 228].

> *(b) . . . documents required to be submitted . . . shall include . . . information with respect to* ***each weapon system*** *covered and shall specifically include . . . development schedule, including estimated annual costs . . . planned procurement schedule … most efficient production rate . . . most efficient acquisition rate. . .* [USC 2004. emphasis added].

Federal Acquisition Regulations (FARs) and department policies and practices (notably the Planning, Programming, Budgeting, and Execution process) also reflect a system-specific perspective. In turn, this perspective enforces the well-known stovepipe behavior of the acquisition system: Resources are allocated directly for a single system and are described in its Program Office Memorandum (POM). Consequently, the acquisition community is less able to provide the *integration* of systems that the operational community seeks.

To move toward a different acquisition model, it will be necessary to change many things, such as the resource allocation process noted previously. Management practices must not be specific to a particular program. Instead, they must take into account the needs of multiple programs and be geared toward systems of systems not single systems.

One approach that has been suggested to support network-centric acquisition is the use of portfolios. Alberts and associates describe two types of portfolios:

> *DoD needs to develop investment strategies and make acquisition decisions based upon portfolios. [One kind is] a portfolio or package of investments that mirrors a Mission Capability Package [MCP]. [Another is] an infrastructure portfolio consisting of a set of capabilities necessary to support multiple MCPs in a specific area such as communications* [Alberts 1999].

One type of portfolio centers on an MCP, while the other type focuses on infrastructure that would support multiple MCPs. Clearly, the integration of these portfolios must also be accomplished.

Portfolio management can be a mechanism to achieve cost reduction by ensuring the opportunity for tradeoffs among important choices while reducing duplication of effort. It thusly brings the management of multiple programs under a common framework that could provide the necessary interoperability in a network-centric context.

Although a portfolio-based approach is expected to provide benefit, it can be viewed as “just another, though larger, system.” Systems of systems are accreted, not designed as a single monolithic entity. As a result, the acquisition community needs to make its processes more flexible by, for example, placing more emphasis on a more rapid and decentralized development mode or incremental acquisition.

Whether a portfolio-based approach will prove viable remains to be seen; other approaches yet to be devised may be necessary. In any event, we must pay attention to the true characteristics of network-centric systems, such as their degree of boundedness. Those practices that implicitly

place a bound on some collection of systems, such as the use of MCP, must address the transition necessary for an unbounded situation.

4 Management Practices

Necessary Condition

Management practices are sufficiently defined and performed to enable the acquisition of systems of systems.

Rationale/Basis for this Necessary Condition

Management practices involve not only the practices used in procurement, such as those related to cost and schedule, but also practices used by industry in the construction of a system. All of those practices must contribute to achieving the goal of network-centric operations, rather than serving only a system-centric perspective. In addition, management practices need to be formed with the recognition that multiple constituents are involved in a network-centric environment. The many possible interactions among those constituents are likely to become more complex in the unbounded environment desired by the operational community.

Discussion

In Section 3, we identified a need for the legal and regulatory environment to support acquisition in a network-centric system environment more effectively. Management practices are derived from the legal and regulatory framework that governs the acquisition and development processes. Given a change to the legal and regulatory environment, there must be a corresponding change in the practices performed by management agents, whether in government or industry.

Organizations in government and industry perform many practices in an acquisition, such as those related to cost, schedule, risk management, and system engineering. These practices are employed by project management entities as well as those engaged in the construction of a system. Different organizations have different goals, functions, and regulatory constraints; the management practices must reflect the differences in constituencies.

Management practices will need to accommodate various facets of interoperability such as the identification and establishment of communication mechanisms among the relevant participants, the sharing of information (both syntax and semantics), and the behavior expected of communicating participants. The necessary changes must extend beyond a system-centric perspective to include the larger context of interoperability in areas such as the following:

- Cost management must realistically account for integration costs, which requires understanding those needs and entering agreements about how those needs will be satisfied and funded. Current regulations often delegate integration costs to a particular program when, in fact, integration costs—like integration itself—must be effectively shared and managed by the relevant constituents.
- Schedule management must account for dependencies and influences among the participants. Appropriate schedule management would include realistic planning and interaction, so that a shared understanding can be developed and agreed to [Meyers 2006b].

- Risk management must account for risk sharing as well as mitigation planning in a wider context. Note the connection to cost here, as mitigation planning requires resources and the source of such resources must be identified and potential conflicts resolved [Meyers 2006c].
- Various practices must be applied to assure that the product created satisfies its performance goals, from verification and validation through user acceptance testing.

Cost, schedule, risk, and performance have often been major concerns for a program manager during the acquisition of a single system. They are clearly interrelated; for example, schedule is a well-known function of cost (and vice versa). In a network-centric environment, it is necessary to effectively manage and uncouple the many possible interactions where multiple programs and constituencies may be involved. Furthermore, in each area, the problems are exacerbated as one moves toward an unbounded environment—as the operational community desires—posing even more challenges to the management of systems that will participate in a network-centric environment. In addition to cost, schedule, risk, and performance, other subjects must be addressed—such as governance, which is discussed in Section 5.

Finally, the role of the operational community must not be disregarded. There must be sufficient interaction between the operational community and the communities related to management and construction in order to achieve a complete success. A noteworthy area demanding this interaction is requirements management [Meyers 2006a]. Integration of requirements is a precursor to integration of systems. Also, current DoD regulations and practices account for Pre-Planned Product Improvement (P3I). This practice must account for, by necessity, the larger goal of achieving interoperability in the operational context, rather than providing a system-centric perspective solution to a perceived local problem [Smith 2005].

5 Governance Procedures

Necessary Condition

Governance is cooperative, distributed across the constituents, and applied selectively.

Rationale/Basis for this Necessary Condition

As system developers and owners realize that their systems are component systems in larger systems of systems, they will gain greater understanding of the need for new governance procedures. Beyond understanding the need, those stakeholders will agree on what governance for network-centric systems looks like and practice appropriate governance procedures. The primary difficulty, and crux of the issue, is that governance (which is about creation and enforcement of policy) can truly only be applied to those things that an individual or group owns. Network-centric systems create a context where no overarching individual, organization, or cooperative body owns everything and can thus govern everything. We can go further: Even if it were possible to find some individual or group in authority to own all the related systems, there are too many of those systems to control or even comprehend sufficiently that they can be controlled [Morris 2006].

Discussion

The network-centric environment will comprise many systems loosely coupled together by a network such as the Global Information Grid (GIG) and capable of interacting with one other in a variety of ways to serve specific purposes. Owners of each component system must engage in some form of collaborative governance with the owners of closely related component systems. Owners must share governance rather than dictate it to one other. The influence by individual constituents in the shared governance will depend on a variety of factors and will vary with time and situation. As component systems become increasingly capable of interacting with one other, they will often participate in missions for which they were not originally designed. Thus, the owners of these systems will need to cooperate, in terms of governance, for the lifetime of such missions, at least. Those owners may have no formal agreement with respect to governance, yet governance must still be effective. To complicate matters more, it is conceivable—even likely—that system owners will find themselves simultaneously participating in multiple missions and interacting with different collections of component systems. It is also plausible that, in some cases, the differing mission groups will agree to different governance processes, complicating governance further for the system in the middle.

To the degree that governance in a network-centric environment can no longer be about strict control, policy must be created and enforced based on peer-to-peer cooperation rather than hierarchical control. Participants thus must use mechanisms based on influence and persuasion rather than direct authority. Mechanisms to influence others to *do the right thing* will be based on motivation or accountability through visibility. One way to motivate self-interest is to make owners accountable for the interoperability (or lack thereof) of their component systems by exposing data on ac-

tions that affect interoperability. With such data available and visible, individuals will be motivated (out of self-interest) to take a wider rather than a narrower view. In addition to motivating the development and operation of a system for the benefit of immediate users, network-centric operations require that developers be motivated by some notion of the greater good, without necessarily knowing what that greater good will be [Morris 2006].

An obvious consequence of the network-centric operational environment is that individual systems will be changing at different rates and times. A corollary is that it will not be possible to coordinate all of these changes to provide phased increments of the whole system of systems. As a result, we see a greater need for policies with respect to the evolution of component systems both with respect to their general interoperability and to their specialized support for shared global objectives. In essence, governance policies will define the etiquette for making changes, providing guidance and rules for what must be done to inform others when a component system changes.

It is clear that diffusion rather than centralization of governance is called for. In one area, however, there will be a tendency toward centralization: the infrastructure supporting the system of systems. Specifically, the infrastructure providers will define the standards for accessing other systems, such as the nature of the registries or metadata repositories and even the communications protocols supported. However, an overly restrictive infrastructure provider will likely find that its expected constituents will use other infrastructures with more acceptable governance. It is inconceivable that there could be one infrastructure to support all of network-centric operations; thus, there is a need for policy with respect to missions that span infrastructures.

For the most part, these points about network-centric operations argue for the development of governance in a collaborative peer-to-peer fashion. Yet, they likely raise other questions. What is clear is that governance for network-centric operations (whether that governance is applied in development or at runtime) will differ from traditionally understood governance. The challenge will be to develop resolutions to the issues and, subsequently, measures of effectiveness for them.

6 Engineering Practices

Necessary Condition

Engineering practices appropriate for evolving (including developing) systems of systems are available, widely understood, and applied.

Rationale/Basis for this Necessary Condition

The ability to create, evolve, test, and operate network-centric systems requires effective engineering practices that recognize and resolve critical aspects of systems of systems that contradict the traditional assumptions that systems are closed, monolithic, globally visible, centrally controllable, or stand alone. Appropriate engineering practices must be developed, validated, and used to evolve systems in a context of understanding systems of systems.

Discussion

Traditional engineering practices assume that

- Need and intended use are known.
- Development is within the control of a single individual or organization.
- Requirements are known and unchanging.[9]
- Systems have clearly defined boundaries with known external parameters or interfaces and explicitly specified interface standards.

Engineering practices based on these assumptions have proven effective in the development, testing, and integration of stand-alone systems for several decades. They remain effective for many of the parts of systems of systems, but for systems of systems as a whole, they are often counterproductive in achieving interoperability. The assumptions were, of course, always simplifications; but they have been sufficiently accurate for most applications of traditional systems.

Increasingly, owners of network-centric systems must undertake integration and integration testing of their own systems. Defense contractors are often unwilling to assume responsibility for integration and system-wide testing. They continue to develop and test system components for which traditional engineering practices are applicable, but they decline to undertake integration activities for which no established engineering practices have proven effective. The underlying issue is that systems of systems cannot be integrated in the traditional sense; instead, they must be composed of constituent parts that are capable of interoperating with each other under varying and sometimes unanticipated conditions.

[9] Actual end-user needs evolve even during development, but current engineering practices are not designed to deal with continuous evolution and either ignore such changes or treat them as discrete modifications to static goals.

Some unique and previously unaddressed aspects of system-of-systems engineering practices relate to systems of systems as a whole and not to their constituent components. Component systems typically are closed systems with known boundaries and clearly defined functionality. Their development can be centrally controlled with all details and aspects of the development visible. Consequently, the components or constituents of a system of systems can be individually developed within the regime of traditional engineering practices providing each is designed to interoperate in a system-of-systems context. Unfortunately, at the systems-of-systems level of network-centric systems, traditional practices are inappropriate because of the increased complexity, the necessity for distributed control, the presence of independent decision making by multiple constituents, the potential for difficult-to-envision indirect effects and emergent behavior, the need to evolve objectives continuously throughout development, and the absence of total system perspective that can be used for end-to-end test and evaluation. Furthermore, the situation is aggravated by lack of operational perspective during development.

New engineering practices are needed that are founded on an understanding of system-of-systems characteristics, applicable to networked systems, and demonstrably effective. Both development and acceptance of these practices will be difficult, because they not only involve new paradigms but also are likely to be in direct conflict with conventional training and intuition derived for monolithic systems. The necessity for development and operation in the presence of uncertainty, the need for dynamic adaptability to unforeseen situations, the ineffectiveness of centralized control, and the inability to avoid emergent effects—all require radically different engineering approaches in the design, implementation, and evolution of systems of systems. Those approaches should adhere to principles such as the following:

- Engineering practices for network-centric systems must emphasize flexibility and adaptability over local optimization.
- Designs must avoid the single points of system failure inherent in hierarchical structures. If none of the monolithic constituents of a system of systems is critical to the system as a whole, then single points of failure within a given constituent are likewise noncritical.
- The traditional concept of static, rarely changing requirements must give way to the capacity to envision use from an operational perspective in a dynamic, uncertain world of continuously changing needs in which systems must dynamically adapt to unforeseen circumstances.
- Emergent effects must be understood, their ill effects avoided, and their benefits exploited to advantage.
- The focus must change from maximizing the number of available features to optimizing long-term satisfaction of evolving operational needs.

As a practical matter, engineering practices appropriate for systems of systems should be developed incrementally, as a growing and evolving body of knowledge is widely shared and increasingly used. The practices should be codified by situation, tradeoff benefit, and risk. Practices should serve as a source book and generalized plan for development and evolution of all DoD

network-centric systems. Special care must be exercised to ensure that engineering practices based on conflicting assumptions are not applied in combination.

7 Technology Base

Necessary Condition

A technology base exists that is capable of realizing the network-centric vision.

Rationale/Basis for this Necessary Condition

The vision of network-centric operations places considerable emphasis on technologies. These technologies range from infrastructure considerations (faster networks throughout the operational environment) to applications that incorporate implementations of concepts such as a common operational picture and sophisticated decision aids. Those involved in acquisition and construction of systems designed to participate in a network-centric environment should leverage the technology base in different ways than in the past, such as by keeping abreast of communication and increasing the speed of technology acquisition.

Discussion

Realizing the network-centric vision depends heavily on technologies to provide the necessary capabilities to the operational community. The technologies are often discussed relative to the infrastructure—faster processors, faster and more mobile networks. However, providing software technologies that meet the network-centric needs offers a considerable challenge. The infrastructure provides the physical connectivity, and the software takes advantage of it.

Although the DoD has relied on the products (and services) of the technology base for a long time, there are changes to consider for network-centric operations. In particular, network-centric operations require a focus on technologies that can be used in the integration of systems—in the extreme case, *dynamic* integration of systems that are not known prior to deployment.

The network-centric vision includes many concepts, one of which deals with the ability of "any actor to task any effector." Achieving that ability requires consideration of remote management. Thus, today's components, centrally managed, will need to become distributed, managed objects capable of being shared across a wide environment. There is therefore a need to perform remote management, with the corresponding need for specification of managed objects, service-level agreements, protocols, and so on. Associated with this problem, there are others. For example, a request to a sensor might require that the schedulability of that sensor be addressed during the course of execution. Correspondingly, recognition and resolution of conflicts among competing interests must be accounted for.

The preceding is but one example of a technology that will be required to achieve the vision of network-centric operations. Many other examples exist, such as technologies that affect the distribution of information (perhaps in the real-time domain) or virtual collaboration among disparate organizations.

To encourage power to the edge, decision aids will become important. Such decision aids can include tools to provide assessment of the (local) environment (i.e., common operational picture), recommend courses of action (such as automated planning and automated doctrine), or initiate and perform operations independent of a human. The growing importance of decision aids reflects the need for more autonomy by the components in the operational environment. In turn, this need leads to the desire for more decision aid tools, such as automated doctrine (a concept realized in the impetus for more robotic objects). In the network-centric context, the challenge to developing the necessary technologies posed by autonomous behavior embedded in a robot capable of dealing with information on a broad scale is considerable.

The desire for more dynamics in the operational environment implies that such dynamism be addressed throughout development (e.g., dynamic scheduling and management). The ability to address semantics in a dynamic environment is related to this issue. In a dynamic environment, the semantics of information—and perhaps of operations as well—will change over time. This line of thought can continue to where consideration of dynamic behavior becomes a goal unto itself. How can a behavior of a system be changed during its own execution? What are the technologies necessary to manage dynamic behavior?

The technology base for network-centric operations will come primarily from industry. This circumstance requires knowledge of the industry community and the ability to leverage results of the technology base improvements. Network-centric considerations warrant that the DoD examine the technology base now from that perspective. It is possible to spur necessary research in network-centric problems through organizations such as the Defense Advanced Research Projects Agency (DARPA) and service-oriented research programs including the Army Research Office (ARO), Office of Naval Research (ONR), and the Air Force Office of Scientific Research (AFOSR). In addition, because of the increased need to interoperate on a wider scale, there may be a need to widen technology base considerations correspondingly. In particular, technology base considerations may warrant leveraging technologies developed by coalition partners. As interoperability continues to gain increased importance, we anticipate a corresponding importance in interoperability through the various organizations that contribute to the technology base.

However, some of the anticipated technological approaches are either immature (such as agent-based approaches or service-oriented architecture) or may not yet exist. In many cases, the desired technologies have not been demonstrated on the envisioned scale of a system of systems. Toward this end, there would be utility in examining technology readiness levels to include a dimension of applicability of the technology to be used in a network-centric environment. Further, the ability to demonstrate the accrual of systems to a system-of-systems context, perhaps through simulation, is a worthy effort.

There must be a way to incorporate the technology base in the acquisition context, notably through contracts. One way that this can occur is for future procurement to include technical feasibility as a key contractual aspect. One might expect that future acquisitions will place greater emphasis on the ability to address specifically the network-centric context, including the ability to integrate possibly unknown sources in a dynamic context. Doing so adds increased difficulty for the specification and evaluation of proposals, not to mention the development of products.

Finally, technology base considerations must be seriously considered by the acquisition community itself. For example, what areas of schedule management or risk management could benefit from increased technological support? In particular, there is a need for technologies that provide greater sharing of information, including semantics, as well as operation on that shared information. Because the principles of network-centric operation apply to both the acquisition and operational communities, the need for technologies to enact those principles does, too.

8 Summary

The effectiveness of systems of systems is influenced by their social and cultural environment, legal and regulatory framework, management practices, governance procedures, engineering practices, and technology base. In those areas, new practices and tools are needed to effectively acquire, develop, test, and operate network-centric systems of systems. The new practices and tools must be built on assumptions that recognize system-of-systems characteristics—such as independent development and independent management of constituents parts, continuous evolution of operational needs, often undesirable emergent behavior, necessity of interoperation with both unanticipated and legacy systems, and the need for adaptation to unforeseen situations (see Figure 3).

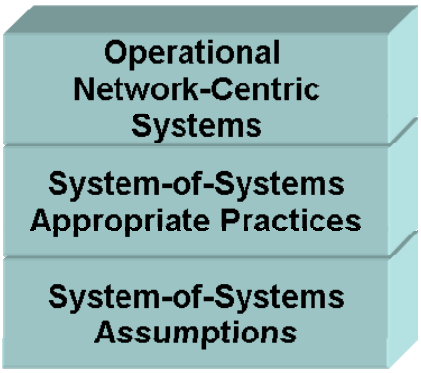

Figure 3: Application of Practices Grounded in Assumptions that Recognize System-of-Systems Realities

In this report, we introduced a necessary condition to which each of those areas must evolve. While positioning these conditions as the desired future states, we note that evolution to them will be gradual and occur at different rates. (See Table 3.) The next steps should include short-term efforts that move in the direction of the identified conditions for achieving network-centric operations in systems of systems. The current conditions also could be refined and extended to additional dimensions, but such efforts will likely have only incremental benefit. Most needed is an idealized vision of how systems of systems can and should be acquired, developed, evolved, and operated in the 21st century. The vision need not be instantiated in detail but must account for all critical aspects of systems of systems and must encompass a full spectrum of business and technical concerns.

Table 3: Evolution Toward Some Necessary Conditions for Network-Centric Operations in Systems of Systems

Area of Significance	Necessary Condition	Incremental Objective
Social and cultural environment	The social and cultural environment in which systems of systems are acquired, developed, used, and evolved motivates collaborative behavior critical to achieving operational effectiveness.	Eliminate aspects of the current social and cultural environment that serve as barriers to achieving necessary reforms in other areas.
Legal and regulatory framework	There exists a legal and regulatory framework to support the acquisition of systems of systems.	Interpret or modify the legal and regulatory framework to better support systems of systems.
Management practices	Management practices are sufficiently defined and performed to enable the acquisition of systems of systems.	Increase interaction between the operational community and the communities related to management and construction.
Governance procedures	Governance is cooperative, distributed across the constituents, and applied selectively.	Aim to develop resolutions to issues and measures of effectiveness.
Engineering practices	Engineering practices appropriate for evolving (including developing) systems of systems are available, widely understood, and applied.	Develop engineering practices appropriate for systems of systems incrementally.
Technology base	A technology base exists that is capable of delivering the realization of the network-centric vision.	Develop a technology base that can address the dynamic, evolving, uncertain, and emergent aspects of systems of systems, as well as their monolithic components.

In examining the necessary conditions, we formed several themes that might also be worthy of further investigation. Among those themes are the following:

- Successful transformation of the DoD acquisition system requires a broader approach. The operational community desires integrated capabilities to meet a mission, but the acquisition community is focused on delivering a system-oriented solution.
- There must be sufficient interaction between the operational community and the communities related to management and construction to achieve complete success.
- Traditional engineering practices and governance procedures are often counterproductive for achieving interoperability, when they are used in combination in systems of systems. They are based on assumptions that do not reflect the reality of larger, more complex, and networked systems of systems.
- The disparity between traditional assumptions and the realities of systems of systems is no longer one of degree or variation but often one of fundamental conflicts. Practices and procedures that are effective for network-centric systems of systems will likely conflict with current system acquisition and development practices that are built on assumptions that are no

longer valid. This problem exists not only for modern systems of systems but also for the social and cultural contexts that acquire, develop, evolve, and operate them.

- The social and cultural environment of a network-centric system includes emergent effects that emanate from the constituents' engineering practices, governance preferences, management practices, and legal and regulatory framework—as well as from the technology base.

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The advantages of systems of systems—such as the ability to adapt to unanticipated and unforeseen situations, eliminate single points of failure, and remain continuously operational while being dynamically updated—guarantee their increasing importance to military and commercial environments. The advent of network-centric systems has served only to accelerate the already prevalent move toward systems of systems.

At the same time, network-centric systems and systems of systems are proving difficult to acquire, develop, test, and operate. Many of them are abandoned before they can be fielded, and fielded systems often fail to satisfy their objectives—demonstrating cost and schedule overruns in their development and sometimes catastrophic failures in operation.

The increasing disparity between the normative (but nonfactual) assumptions that underlie current practices and tools used in the acquisition, development, evolution, and operation of systems and the realities of actual systems of systems contributes to those problems. Effective practices and tools for the acquisition, development, and operation of systems of systems have not yet been developed. Suggesting a context in which those practices and tools can be developed, this technical note proposes necessary conditions—statements of what the desired future state should be—in six areas that influence the effectiveness of network-centric systems and systems of systems: (1) social and cultural environment, (2) legal and regulatory framework, (3) management practices, (4) governance procedures, (5) engineering practices, and (6) technology base.

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