Systems Engineering in the Information Age: The Challenge of Mega-Systems

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Abstract

As it makes the transition from the industrial age to the information age, the Department of Defense, like other government agencies and indeed like the global business community as a whole, is moving aggressively to leverage and capitalize on advances in information technologies. The result is a clear trend away from stand-alone component systems to ones that are richly interconnected and increasingly interdependent. We call these "mega-systems." This paper focuses on the engineering of this class of systems which is characterized by increasing scale, the nature and pace of change of the technologies involved, the complexity of system interactions and, perhaps most important, the fact that a single organization rarely owns and has complete control over the mega-system. We hypothesize that engineering these mega-systems is inherently different from engineering large-scale but essentially well-bounded monolithic systems. We develop a framework to understand the differences between well-bounded systems and this new class of systems. On the basis of these insights, we propose an approach to engineering mega-systems that emphasizes experimentation over rigorous requirements definition and continuous evolution over a "grand design".

Introduction

Demand for Agile, Adaptive Responses

Several factors are converging to fundamentally change the nature of the systems that are developed and fielded to the U.S. military forces.

The strategic environment demands agile and adaptive response to a wide range of threats and missions. Responding to this uncertainty is the emerging military concept of network centric warfare[1] which seeks to leverage information as a competitive source of power. The information revolution, on which this concept is based, provides the tools by which we can interconnect a wide range of elements and provide them timely information. Finally, there are significant changes in the processes by which the Department of Defense (DOD) intends to acquire necessary military capability.[2] These converging trends lead to a growing emphasis on large-scale, richly interconnected capabilities that bridge traditional organizational and functional boundaries.

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[1] Alberts, David S., John J. Garstka, and Frederick P. Stein, *Network Centric Warfare*, 2nd Edition, CCRP, 1999.

[2] The DOD is moving from a bottom-up requirements-based process to a top-down capabilities-based process and is implementing the Joint Capabilities Integration and Development System (JCIDS). CJCSI 3170.01C and CJCSM 3170.01 can be found at http://www.dtic.mil/cjcs directives.

Richly networked joint and coalition forces, capable of operating at high tempos and able to adapt to and leverage opportunities as they emerge, are hallmarks of the emerging future force. Many of these characteristics were evident in Operations Enduring Freedom and Iraqi Freedom. The commercial world values similar characteristics. The ability to sense, process and make mid-course corrections in response to real-time intelligence is a competitive advantage not just in combat but also in business. In the DOD, we talk about "coherently joint"; in the commercial world, the term is the "extended enterprise."

The extended enterprise is defined as "a networked supply chain that integrates partners, suppliers, manufacturers, retailers and customers in a seamless, Internet-based communications system."[3] More important, it entails ***collaborative*** behavior among business partners and thus crosses multiple enterprises. The benefits of such collaborative behavior translate directly to the bottom line – leaner inventories, lower working capital, higher profits, and better customer service.[4]

Implications for Systems and Programs

How do these trends affect the systems that are and will be developed to meet the needs of the emerging operating environment, be it in government or commercial sectors? We see several significant implications.

First, we expect to see a continuing trend toward increased program ***scale and scope*** as single acquisition programs encompass what in the past would have been separate acquisition efforts. Commercial and government enterprises are also seeking to integrate separate, often isolated, operations, processes and information. In so doing, they take an enterprise-wide perspective on how they organize and operate. Decisions about investments in individual information technologies, previously made locally, are now being made at the enterprise level.

A related trend is the ***convergence of previously separated systems***. Programs that were previously separately managed are being organized into cooperative efforts. For example, the Global Command and Control System has until now had several variants, each focused on meeting the particular needs of the funding organization. The current plan is to converge these separate efforts (joint, army, maritime, and air force) into a common engineering and development effort.

The combination of increased scale and scope and convergence of previously separated systems translates into systems that will ***cross traditional boundaries***. These boundaries can be organizational, functional, or disciplinary.

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[3] http://business.cisco.com/glossary

[4] Davis, Edward, and Robert Spekman, *Introduction to the Extended Enterprise: Gaining Competitive Advantage through Collaborative Supply Chains*, chapter published on-line at www.informit.com/isapi/product_id., Dec 12, 2003

Information technologies remain at the core of these emerging, large-scale systems, as developers seek to leverage commercial technologies and common, often commercial, standards. To that extent, there will be a continued growth in ***integration*** and a commensurate decline in custom developments. The integration challenge will continue to increase as the efforts will focus on integration of heterogeneous components, separately developed and managed. Not only do we expect the components to be diverse, but the development activities will also be distributed across multiple, often physically dispersed, activities that may or may not report within a common organizational structure.

Further, these systems will need to accommodate ***rapidly evolving needs***, organizational patterns, and technologies. We cannot expect to be able to articulate, with any reasonable precision and certitude, a set of required attributes likely to remain constant over the course of the development effort. Rather, we fully expect that the needs will evolve in parallel with, and often in response to, the evolution of the systems themselves.

Finally, these systems are expected to be increasingly ***complex.*** The flip side of having systems that accommodate multiple communities and interests and that are themselves evolving is that the system behavior will not always be predictable but instead will emerge as a result of the interaction of the components.

The Challenge for Systems Engineering

We have briefly sketched out a view of the near future – rapidly evolving, large-scale, massively interconnected systems intended to bridge traditional boundaries. These systems are not just scaled-up versions of the systems that we have been developing in the latter half of the twentieth century but, we believe, a significant departure. The practice of systems engineering has evolved over the last half century and must continue to evolve to meet the challenges of this new class of systems. We have concluded that the traditional processes and practices apply only in part to this new class of "mega-systems." We further conclude that a complementary set of practices and processes is needed.

A Framework for Exploring Mega-systems

A Working Definition

"Mega-systems" are large, potentially complex systems that are formed by the integration of separately developed systems to provide functionality beyond that achievable by their component systems. Their salient characteristics are embedded in this proposed definition.

First, they are large, man-made systems. While "large" is clearly a relative term, we mean something generally greater in scope than either an assembly[5] or even a large, but unitary, system such as a radar or even an entire submarine.

Second, they are potentially complex. By "complex," we do not mean that they are either intricate or difficult to construct (which they often are), but rather that they exhibit complex behavior, both internally among their components and as a whole.

Third, these mega-systems are rarely developed as a monolithic whole, but are formed through the process of integration; that is, they are "put together." By integration, we mean the progressive linking and testing of system components to merge their functional and technical characteristics into a comprehensive, interoperable system. Note that integration includes but is not limited to the ability to share or exchange data.

Finally, these systems often have a significant human dimension, both cognitive and social, which contributes both to the complexity of behavior and to the continuing evolution of the mega-system as it operates in its environment.

The Framework

The above discussion suggests that there are multiple dimensions to understanding mega-systems. We identify four key dimensions.

- The system and its behavior, ranging from linear to complex
- The decision making environment, ranging from unitary to pluralistic
- The mission environment, ranging from stable to fluid and evolving
- The acquisition environment, ranging from single to multiple acquisitions

The framework, shown in Figure 1, highlights the first three of these dimensions.

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[5] An assembly is a collection of components and modules combined into a single unit. A typical assembly may perform a well-defined function within a larger system, hence constituting one of its subsystems; it can also be an independent, self-contained product that performs a single function of a limited scale. Examples of assemblies include a radar receiver or a computer hard disk. See Shenhar, Aaron, "A New Systems Engineering Taxonomy," in *Proceedings of The 4th Annual International Symposium of The National Council on Systems Engineering*, San Jose, CA, August 1994.

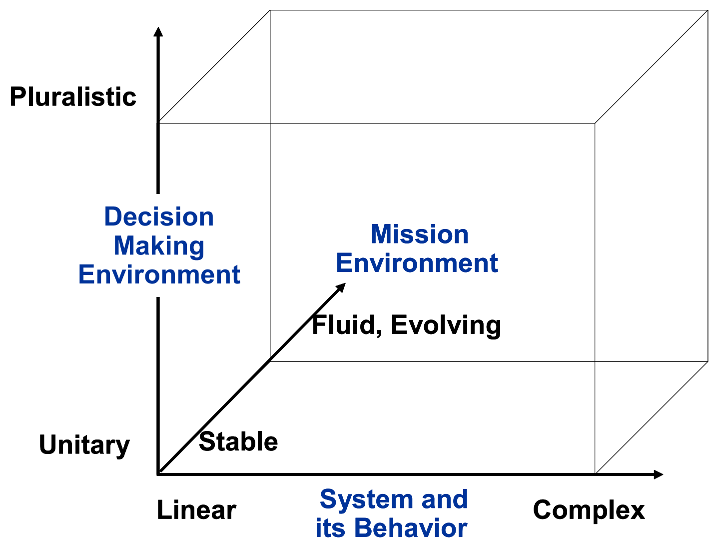

Figure 1: The Basic Framework[6]

The first dimension, *System and Its Behavior*, distinguishes the behavior of the system in terms of the degree of complexity.[7] Linear systems exhibit behavior that is regular, well-understood and, to a large extent, predictable. They follow well-established rules of behavior, such as laws of physics or mechanics. They are relatively closed to the environment, in that their behavior is not significantly affected by events external to the systems. Finally, their component elements are not purposeful; in other words, they exist only as part of the larger system and do not follow their own independent goals.

In contrast, not all the attributes and behavior of a complex system are directly observable and not all the observable interactions are understood. Second, they do not follow well-ordered, predictable rules of behavior. Solutions to specific problems may well result in totally unexpected responses. Third, complex systems exhibit *emergent behavior*, in that the interaction of components results in behavior that can not be only unexpected but sometimes also quite different from the behavior of the components themselves. Thus, it may be difficult to predict the effects of a change without actually implementing it. Finally, complex systems interact with their environment and thus evolve over time. Complex systems cannot be understood merely by decomposing them into their constituent elements and separately analyzing these elements. Instead, the focus is on the nature and effects of their interactions not only on other component systems, but also on the whole.

The second dimension, *Decision Making Environment,* addresses the extent to which decision makers agree as to the goals and objectives of the system as a whole. Unitary decision making implies agreement. Decisions are made and implemented in accordance with these common goals and are thus acceptable to all stakeholders. In contrast, decision

[6] This framework is an extension of ideas presented by Michael Jackon and P. Keys, "Towards a System of Systems Methodologies, " [sic]. *J. Opl. Res. Soc.*, Vol 35, No. 6, 473-486, 1984.

[7] Systems in which human and group interactions dominate are more likely to exhibit complex behavior; systems which are more machine-like are more likely to exhibit linear behavior.

making is pluralistic if there is little or no agreement as to the goals and objectives of the mega-systems and decision makers instead focus on their local concerns. In such instances, the few decisions made will address only those aspects on which the various stakeholders can, in fact, reach agreement. On occasion, decisions can be imposed on the stakeholders, but in these cases either blatant or more subtle pushback could be expected.

The third dimension is the *Mission Environment*. It can range from one that is stable and enduring, in which the processes, procedures, and relationships are well understood and likely to evolve slowly, to one that is fluid and dynamic, where participants, their interactions, and the "rules of the game" change significantly and rapidly. In a fluid, evolving environment, understanding today's patterns of interaction helps little in anticipating future patterns.

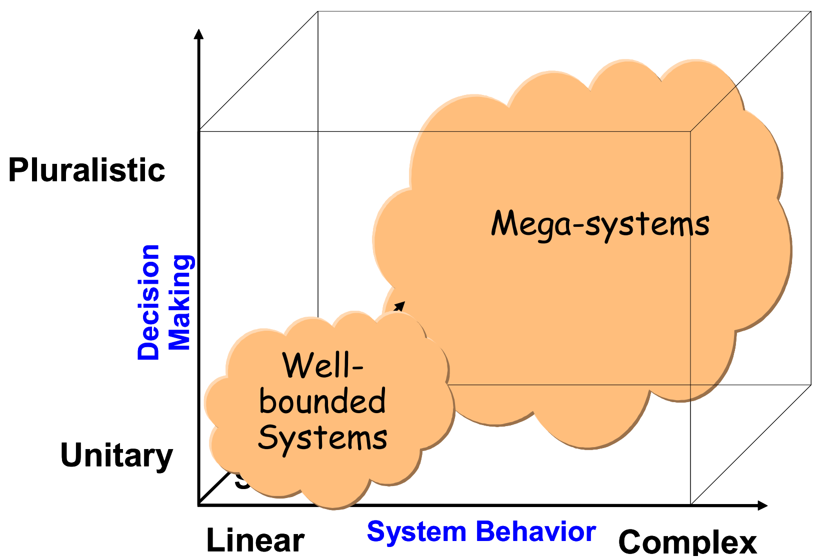

Figure 2: Well-bounded Systems and Mega-systems

As you move from the lower left region, where system behavior is linear, the decision making environment is unitary, and the mission environment is stable, the behavior becomes more complex, more unpredictable and more fragmented. The former is termed the region of "well-bounded" systems; the latter is the region of "mega-systems."

Well-bounded systems lend themselves best to traditional systems engineering and development approaches, whichCheckland has termed these approaches "hard systems thinking". Such systems are based on "the assumption that the problem task they tackle is to select an efficient means of achieving a known and defined end."[8] This, in turn, is predicated on having well-defined, precise, and stable requirements. Because of the linear nature of the system's behavior, traditional systems engineering assumes that overall functions can be decomposed and allocated to components with the expectation

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[8] P.B. Checkland, "The Origins and Nature of 'Hard' Systems Thinking," *J. Appl. Systems Analysis*, Vol. 5, 1978, 99–100.

that the components and the whole will behave as expected. The engineer can predict and therefore has some measure of control over the technical interactions of the system's component elements. And because there is at least written agreement as to goals and objectives, the manager can make decisions to maximize the achievement of these desired outcomes.

In contrast, engineering mega-systems entails dealing with top-level requirements that are difficult to articulate with desired precision, are often internally contradictory and will certainly evolve along with user expectations. The engineering process also must deal with functionality and behavior that will emerge from the interaction of the components without specific direction of the engineer. Because it is unpredictable, such behavior is difficult either to engineer in or engineer out. Mega-systems engineering also must often deal with the challenges of working across program boundaries, which may entail competition for limited resources and between alternative solutions.

Examples of Mega-Systems

A wide range of activities can be viewed as mega-systems, encompassing both efforts that set out to compose a mega-system from elements that were previously developed as stand-alone systems to ones that set out to design a fundamentally new capability, in effect, from the ground up. The Air and Space Operations Center and law enforcement information sharing are examples of the former while the Army's Future Combat Systems and the Electronic Product Code Network are examples of the latter.

The Air and Space Operations Center (AOC) is defined as the Combined Force Air Component Commander's "weapon system" for commanding air and space forces.[9] It consists of the staff (roughly 1000 to 2000 personnel); the processes involved in planning, tasking and monitoring all air operations in a theater of operations; and the enabling technologies. These, in turn, consist of over 80 different elements – including infrastructure, applications, servers and databases – and have been described as "different pieces representing different fiefdoms and principalities."[10] These elements lack a common conceptual basis, common funds to solve cross-cutting problems, or common control or management. In addition, individual elements have many "customers" of which the AOC is only one, and have evolved independently at different rates.

Since 9/11, there has been a clear mandate to improve information sharing among federal, state, and local law enforcement agencies. The scope of this effort potentially encompasses not only multiple federal agencies but also roughly 18,000 state and local law enforcement organizations. Today, these organizations use hundreds of different systems, both home-grown and commercial. But perhaps more challenging than the technical aspects are the legal and cultural barriers to information exchange. These barriers include not only growing privacy concerns about sharing information but also mutual distrust among different organizations, particularly regarding investigative data.

[9] Rudolph, Col John, "AN/USQ-163 Air & Space Operations Center (AOC)", briefing.
[10] Norman, Douglas O., and Michael L. Kuras, "Engineering Complex Systems", chapter in *Complex Engineered Systems*; Purseus, (in press).

The Future Combat Systems (FCS) is the Army's key transformation program. It is intended, over time, to replace the current inventory of Abrams tanks and Bradley Fighting Vehicles with a new family of lighter weight, more deployable but equally as lethal and survivable platforms. It is described as "a networked "system of systems" – one large system made up of 18 individual systems, plus the network, plus the soldier."[11] These individual systems encompass not only manned ground vehicles but also unmanned ground and air platforms. (Of note, some in the Army are now referring to the FCS program as 1+18 suggesting that the network that will link the various platforms together takes precedence).

The Electronic Product Code (EPC) Network is an open standard, global network using low-cost radio frequency identification (RFID) tags to track items throughout the supply chain. It was developed over a period of four years by a consortium of universities, headed by the Massachusetts Institute of Technology, and was cooperatively funded by a sponsors that included retailers, consumer packaged goods manufacturers, and technology vendors. By allowing pallets, cases, and even individual items to be tracked globally, this technology can potentially transform the supply chain. Adoption of the technology has been greatly accelerated by a mandate from Wal-Mart, requiring its top suppliers to begin implementation in 2005. At the same time, vocal concerns from privacy advocates have impacted some planned field trials.

Preliminary Observations

One of the challenges of examining these and other similar mega-systems is that they are all still in various stages of development and therefore it is difficult to consider them as formal case studies. However, several observations can be made.

First, no single engineering technique is common to these efforts. For example, the AOC has attempted and subsequently rejected using traditional systems engineering techniques. FCS is following the Defense Acquisition University's "Systems Engineering Fundamentals" as a guide for the program. The EPC Network efforts, perhaps because they were more oriented towards technology development, did not explicitly follow any methodology but did emphasize early prototyping and field trials.

Second, there is no common organizational framework. There is a Special Project Office in charge of the AOC but, in effect, there are many component systems that are managed by different organizations responding to different constituencies.[12] The FCS program has hired a Lead Systems Integrator who has total systems integration responsibility and is responsible for managing the identification, selection and procurement of major systems and subsystems. By contrast, improved law enforcement information exchange is

[11] http://www.boeing.com/defense-space/ic/fcs/bia/about.html

[12] The Air Force is in the process of selecting a Lead Service Integrator. This LSI is not expected to provide specifications of components or interfaces. Instead, the LSI is expected to establish and oversee an environment in which components are gradually but continually conceived, implemented, fielded and evaluated. See http://herbb.hanscom.af.mil/esc_opps.asp?rfp=R495

accomplished by a number of separately managed initiatives while the EPC Network effort was organized as a collaborative undertaking that was funded by a wide range of industry sponsors, a number of whom were direct competitors.

Third, organizational, cultural, political and other "soft" issues have had critical, often confounding impacts that require engineers to refine their visions and adjust their plans.

Fourth, while it is possible to state goals as broad visions, it is often difficult to translate them into clear and unambiguous statements of specific desired outcomes and to hold those outcomes constant in the face of changing technologies, expectations, and constraints or even new opportunities.

What Seems to Work Well… and Not as Well

Techniques that seem to work for mega-systems include:

- Engineering enablers, including architectures, visions, and plans (as long as they are viewed as means rather than the end itself)
- Techniques that facilitate continuous, broad-based involvement by representatives from multiple organizations, including Integrated Product Teams and collaboration environments. These work best when there is visible support from the senior leaders of the represented organizations.
- A real consensus around the basic infrastructure and the key design tenets.
- Integration facilities, both virtual and real, that allow for discovery and exploration of unanticipated behaviors.
- Early field trials and experiments to help explore how the elements work with one another and to introduce "real world" dimensions.
- The critical role of a charismatic "champion" who is able to forge alliances across organizational boundaries and overcome process limitations.

Techniques that do not seem to work as well:

- Efforts to develop detailed and comprehensive requirements and specifications[13]
- Insufficient attention to understanding the larger environment in which the mega-system will operate and evolve; not involving all key stakeholders.
- Multiple stakeholders, separate agendas, distrust
- Establishing unnecessarily complex organizations; emphasizing process
- Developing a grand design and expecting it to remain constant in the face of technology obsolescence, changing user expectations, and evolving mission environments
- Technical solutions for inherently non-technical problems (e.g., privacy)

[13] Detailed requirements are developed to scope contractor and subcontractor efforts and associated costs. Alternative contract management approaches might include incentive fees which reward enablers of mega-system development as well as management reserves for course corrections identified though incremental experimentation. This is a substantial topic onto itself and, while it is outside the scope of this paper, warrants further exploration.

- Acquisitions across program boundaries

Implications for Engineering Mega-Systems

Traditional systems engineering is centered on developing products that have well-defined boundaries and meet pre-conceived specifications. Engineering mega-systems is considerably messier. It must deal with ambiguous boundaries, continuously changing expectations including new opportunities that were not initially envisioned, technology obsolescence and emergence, and a shifting mix of cooperation and competition among participants and stakeholders. However, it is important to emphasize that mega-system engineering does not replace traditional systems engineering. To the extent that mega-systems encompass well-bounded elements, traditional systems engineering practices will continue concurrently with the practices that will evolve around mega-systems engineering.

The following is a preliminary set of implications for mega-systems engineering. These too will evolve as we gain experience with the challenges of this class of systems.

Implications #1. *Mega-systems engineering should place less emphasis on having a comprehensive, detailed set of requirements and specifications at the onset and more emphasis on incremental experimentation and trial*. Discovery experiments, using early prototypes, should be conducted to explore the boundary between linear and complex behavior and to provide early insight into those aspects of the mega-system that are subject to emergent behavior. Field trials should be used to gain insight into evolving user expectations, gather lessons learned from the real world, and better understand how the capabilities of interest fit into the larger context.

Implication #2. *Consensus around the enabling infrastructure and design tenets is the structured piece of the unstructured problem.* This defines the minimum set of standards and architectural guidelines necessary to allow different elements of the mega-system to work together and to evolve over time. It enables the ***guided*** evolution of the mega-system in the absence of a comprehensive grand design.

Implication #3. *Mega-systems engineering should make maximum use of existing collaborative engineering tools and practices and encourage the evolution of new techniques.* Collaborative engineering practices, including groupware tools, enable dispersed teams to work on solutions to common problems. These tools and techniques need to be augmented by additional tools and techniques that encourage collaboration among participants who view themselves are competitors. Institutional and contractual incentives to foster collaboration will probably be required.

Implication #4. *Capabilities that are deemed useful should be spiraled off to the user.* Capabilities that can be provided earlier should be offered to the user in a meaningful "chunk." This would provide not only a measure of capability that was not previously available, but also provide a critical mechanism to better understand user preferences and expectations.

Implication #5. *Mega-systems should be encouraged to evolve in situ.* Users will inevitably adapt the capabilities that are provided to them to meet their particular needs and, in so doing, will introduce new complexities, both in how they use the technology provided and how they accomplish their missions.[14]

Concluding Thoughts Intended to Provoke

Network centric operations and extended enterprises entail thinking differently about the underlying "business" process. By analogy, they also encourage us to think differently about how we structure and implement solutions. Just as long cycle times and deliberate planning are hallmarks of industrial-age business strategies, perhaps long acquisition cycles and grand designs are the hallmarks of industrial age product developments. And just as self-synchronizing organizations are emerging as the hallmark of the information age, perhaps self-synchronizing developments based on agreed-to goals and a common infrastructure – and not on detailed specifications – will become the hallmark of mega-systems engineering.

[14] Woods, David D., "Steering the Reverberations of Technology Change on Fields of Practice: Laws that Govern Cognitive Work", Plenary Address, Annual Meeting of the Cognitive Science Society, August 10, 2002