★RMS PARTNERSHIP★

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Reliability, Maintainability, Supportability: Emergent Properties of Complex Adaptive Systems

by Robert M. Flowe

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Introduction

The Department of Defense (DoD) has a love-hate relationship with complexity. On the one hand, the DoD seeks to maximize the effectiveness of its combat forces by pursuing Joint Operations which requires tight integration of resources (collectively termed "Joint Capabilities") regardless of the service / agency affiliation(s) of participants. The increased agility and responsiveness that Joint Capabilities permits is a desirable "emergent" behavior of the joint force. On the other hand, the operational, engineering, and programmatic complexities imposed by the desire for Joint Capabilities present tremendous challenges that affect every aspect of the DoD enterprise. In our pursuit of effective joint capabilities, we have created bewilderingly complex networks of semiautonomous interdependent entities ("programs" or "systems"), which collectively form a complex adaptive overarching system subject to emergent behaviors that are both difficult to predict and control. The DoD Acquisition process is no exception.

Acquisition Implications of Joint Capabilities

Joint Capabilities impose interoperability requirements across the spectrum of Doctrine, Organization, Training, Materiel, Leadership, Personnel, and Facilities (DOTMLPF). The acquisition process, which focuses mainly on the "materiel" aspect of DOTMLPF, must consider the flow-down of joint capability requirements to the systems which make up the capability, and how these requirements are implemented throughout the acquisition life cycle. Although operational requirements are specified in a joint context, and the overall acquisition process is defined by DoD-wide acquisition processes and regulations, the actual implementation of the acquisition process is devolved primarily along service / agency boundaries. Each service has its own acquisition organization, rules, and regulations. Although the Joint Capabilities Integration and Decision System (JCIDS) attempts to counteract the influence of service affiliation in the mapping of joint requirements to acquisition programs, there is no explicit alignment of the acquisition process to the design of the joint operational capabilities. Significantly, the DoD resource allocation process also aligns with the services, so each has its own acquisition budget that is allocated in light of service-perceived priorities (with considerable influence from DoD-level oversight). Therefore, the DoD acquisition process must manage and oversee the interaction of the multiple independent entities which are individually tasked to develop, procure, field, and sustain the constituent systems such that the end-to-end joint capability is achieved. Furthermore, responsible resource management

CONTENTS

RMS Partnership Newsletter
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Peas in the Same Pod? U.S. Automobile & Defense Industries

by Russell A. Vacante, Ph.D.

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There is one characteristic that the U.S auto and defense industries have in common that has contributed to their current global competitive difficulties. This is a macro, or big picture, type of issue that if not collectively addressed by the government, industry and academia, could further dull the cutting edge of U.S. world leadership. The issue is often referred to as **change management**. From an institutional perspective, managing and implementing change involves a willingness of senior leaders to recognize and accept that lasting and meaningful change requires a tolerance and willingness, on their part, to reshape their institutions from the bottom up and top down. The U.S automobile and defense industries are peas in the same pod with respect to this observation.

Many professionals within both the automobile and defense industries are familiar with the challenges associated with career and employment change. We have taken change management classes, endured the uncertainties that accompany institutional

{Editorial cont., 9}

requires the establishment of, and management to, cost, schedule, and performance baselines when developing required capabilities with corresponding documentation to ensure transparency and accountability.

Complexity and Emergence

As Defense acquisition becomes more focused upon the "mash-up" of the various, diverse, and generally non-interoperable elements of Joint Capabilities, the interactions among the participating entities will drive a larger proportion of overall effort. While complexity will necessarily increase with the number of interacting entities, it is the semi-autonomous aspect of these entities that creates the potential for "emergence." A Swiss watch is complex, since it has many exquisitely interacting elements. But, though complex, the interacting elements do so in an explicitly predictable, deterministic manner, so the behavior of the integrated "system" is itself predictable and deterministic. But what if the interacting entities have some "fuzziness" in how they respond to their environment? If their behavior is individually stochastic or probabilistic, then the potential for uncertainty in their aggregate behaviors exist. The collective effect of numerous decisions and actions among the semi-autonomous yet interdependent actors sets the stage for so-called "emergence." Emergence, loosely defined, refers to unanticipated features and behaviors that "emerge" only as individual entities are aggregated and interact. Emergence occurs from the collective effect of local rules and incentives which drive actions of the individual entities, as each responds to its environment and the actions of its neighbors. These local rules tend to be based upon simple assumptions regarding the boundary conditions with its external partners and the environment. These local assumptions create the potential for instability at the collective level, which can induce dramatic swings in collective measures of performance and effectiveness.

Emergent Properties and Behaviors

Complex adaptive systems such as these can have "emergent properties" such as instability under certain conditions. The existence of emergent properties may give rise to "emergent behaviors" when the necessary conditions exist and a triggering event causes departure from equilibrium. Emergent properties exist only at the aggregate level and are not obvious extrapolations of the properties of the individual elements. Though these emergent properties (such as instability) may exist, they may not be observable until a triggering event causes outward behaviors to manifest themselves. An example of this is the global financial crisis we are currently experiencing. In this case, seemingly isolated institutions (banks, credit rating bureaus, insurance firms, municipal governments, etc.) were in fact coupled via explicit and implicit market and risk trading mechanisms, that were influenced by interacting incentive structures that drove individual actions in such a way to create global financial instability (an emergent property). The evidence of this instability was fairly muted (i.e., not observable) until the "triggering event" of a declining US housing market precipitated the collapse of the financial and credit markets (emergent behaviors). Throughout the emerging disaster, one could watch as individually rational decisions propagated and amplified the cascading consequences across the "network" of interdependent institutions, resulting in collectively "irrational" consequences. It is instructive to note that although the participants may have been aware that their actions would neither protect themselves from disaster, nor would avert the broader crisis, they were powerless to behave otherwise. The local-optimization rules forced them to act "irrationally" (in a global context). The case in point here is the major lending banks' response to increasing loan defaults—these banks clearly understood the implications of a global shutdown of credit, but their local rules required them to hoard capital against their potentially bad debts, and therefore they refused to lend, even to ostensibly responsible borrowers. Thus their local optimization rules trumped global rational behavior and deepened the crisis.

This serves as a cautionary tale of the potential downside of complex adaptive systems. While global productivity and wealth was certainly increased by the credit-fueled "bubble," the very interdependence spurring that wealth was the mechanism by which the subsequent crisis propagated across the globe. Similarly in the pursuit of Joint Capabilities, the desirable emergent property of agility, for example, will also bring the potential for negative emergent behaviors resulting from the same underlying complexity and interdependence. So this is the "double-edged sword" of increasing interdependence and net-centricity: greater agility, flexibility, etc., but also increased risk of negative, potentially harmful, emergence such as instability and cascading failures. Thus as we transform to a net-centric, capability-based paradigm, the issue of reliability, maintainability, supportability, security, integrity, etc., of the overall enterprise are of paramount importance.

Reliability, Maintainability, and Supportability as Emergent Properties

So if reliability, maintainability, and supportability (RMS) are emergent properties of the aggregated capabilities, what role does the RMS engineer play? To answer this, it is important to note that the classical treatment of RMS is primarily aimed at the individual system. Stochastic models of RMS applied at the system level can help understand emergence in that context. However, even these stochastic models are based upon assumptions regarding system design and utilization, which in turn depend upon assumptions regarding operational environment and other external factors. These assumptions become tenuous in a complex adaptive system and, although risk transferring methods such as performance based logistics may mitigate risk locally, the potentially unexpected behaviors of the aggregate may violate the underlying assumptions and result in degraded RMS properties of the individual system, and the collective capability as well. So even if RMS engineers are not explicitly "responsible" for assessing the collective properties enterprise-wide, they may still experience the effects of emergence at their system. This is analogous to the insurance company that assessed the risk of underwriting the infamous "credit default swaps" as being low, because who could possibly imagine these blue-chip companies going bankrupt? So, even at the individual system level, RMS engineers should be very aware of the assumptions that underpin their analyses.

Even more challenging is assessing the RMS of the aggregate capability. Rigorous methods for assessing emergent RMS properties at the capability level are not available and methods for predicting emergent behaviors are not well developed. However, the consequences of our adversaries exploiting emergent vulnerabilities clearly make this a priority. General rules for describing and predicting RMS and other emergent properties at an enterprise level are necessary. In this, network and graph theories may provide a useful tool set.

Application of Network Theories to Joint Capabilities Acquisition

In application to the analysis of Joint Capabilities, an arbitrary collection of interdependent programs can be considered a "network." The term "network" refers to individual entities which interact with one another for the purposes of exchanging resources for their individual and collective benefit. The DoD is developing methods for making these interdependencies among systems and programs explicit. For example, methods for constructing integrated architectural models that capture the interactive aspects of system elements provide an opportunity to consider the network-like aspects of interdependent programs individually or as compositions within systems of system, portfolios, or integrated capabilities. In addition, the evolution of model-based acquisition methods that implement standardized notation and data formats is expanding the arsenal of analytical tools that can be brought to bear. Early indications suggest these approaches are potentially fruitful.

One study sponsored by our office has examined network properties of acquisition programs by mapping interdependencies and resource flows among programs (fig 1). The evidence suggests that the DoD acquisition enterprise may be evolving over time from a random network to a scale-free network (fig 2 on following page), and may be achieving greater efficiency as a result. Complementary work examines measures of complexity and interdependence among systems and its relationship to program cost (fig 3 on following page). This study has provided empirical evidence, based on an exclusively DoD-related data set, that interdependence is correlated with program development cost, and that relatively straightforward nonlinear relationships describe the emergent patterns of interactions among them (fig 4 on following page). Discovery of such relationships opens the possibility of predicting emergent properties and potential for emergent behaviors. This conceivably changes the game from the DoD reacting belatedly to unanticipated emergence to proactively "designing in" beneficial emergence while mitigating associated risks.

Understanding Emergent Properties of RMS

The complexity of interactions among the elements of joint capabilities may confound traditional system- and program-centric acquisition management methods. Emergent properties such as capability-level RMS are particularly susceptible to these dynamics. However, by changing the terms of reference from system-centric to explicitly considering the entities and their formally-defined interactions, we open the door to examining the emergent properties and dynamic behaviors from a network analysis perspective, and thereby can use these principles to gain some insight into potential emergent properties. In this way we can influence the behaviors of individual entities to support the desired Joint Capabilities objective with the underlying strategic RMS that these capabilities demand. ★

About the Author

Robert M. Flowe currently serves on the staff of the Deputy Director for Strategic Initiatives (SI) in the Systems and Software Engineering (SSE) directorate of the Office of the Deputy Under Secretary of Defense for Acquisition and Technology. Mr. Flowe leads the Strategic Studies program and coordinates investment in research to advance the state of the art for systems engineering in the DoD. In this role, he oversees the research agenda for the Systems Engineering Research Center (SERC), a new DoD University-Affiliated Research Center dedicated to system engineering research. Prior to his current position, Mr. Flowe served as senior operations research analyst on the staff of the Deputy for Resource Analysis, Office of the Secretary of Defense (OSD), Program Analysis and Evaluation (PA&E), principally supporting the Cost Analysis Improvement Group (CAIG). During his seven years on the CAIG staff, he led and supported independent cost analyses on a variety of programs including submarines, space launch vehicles, command, control, communications, computers and intelligence (C4I) systems, and automated information systems. Mr. Flowe retired from the United States Air Force in 2003, after having served in a variety of acquisition, engineering and operational positions relating to space launch; intelligence and information operations, specializing in systems and software acquisition. While on active duty, he served on the faculty of the Defense Acquisition University, where he managed and taught the Intermediate Software Acquisition Management Course. Mr. Flowe has a B.S. in Aerospace Engineering from Virginia Tech, and a M.S. in Software Systems Management from the Air Force Institute of Technology. Mr. Flowe is Level III certified in both Program Management and Systems Planning, Research, Development and Engineering (SPRDE)/Program Systems Engineering.

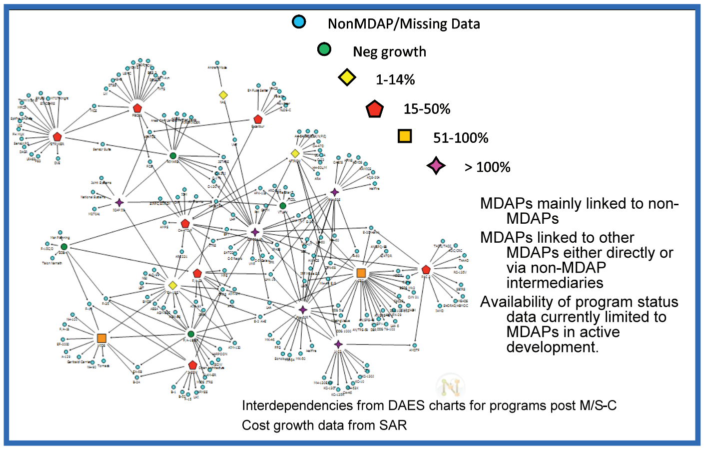

Figure 1 - Program Networks among MDAPs

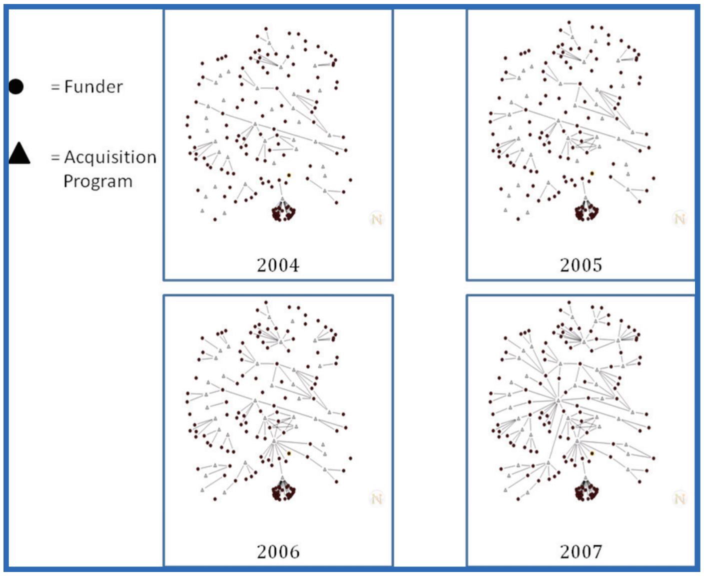

Figure 2 - Emergence of Network Patterns among MDAPs 2004-2007

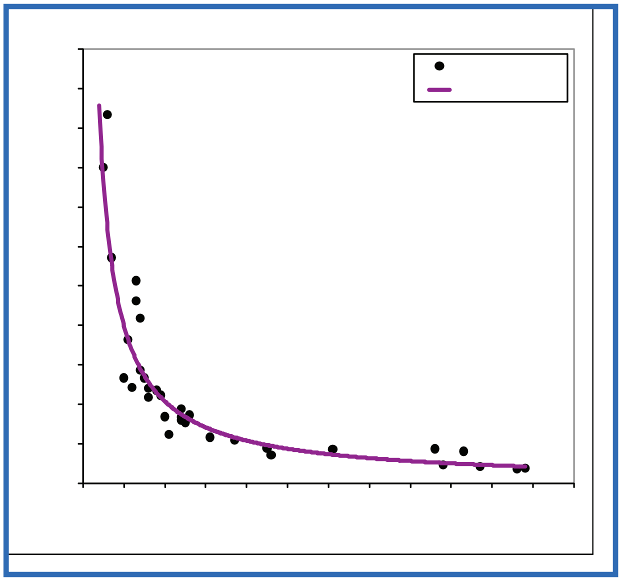

Figure 3 - MDAP Measures of Interdependence

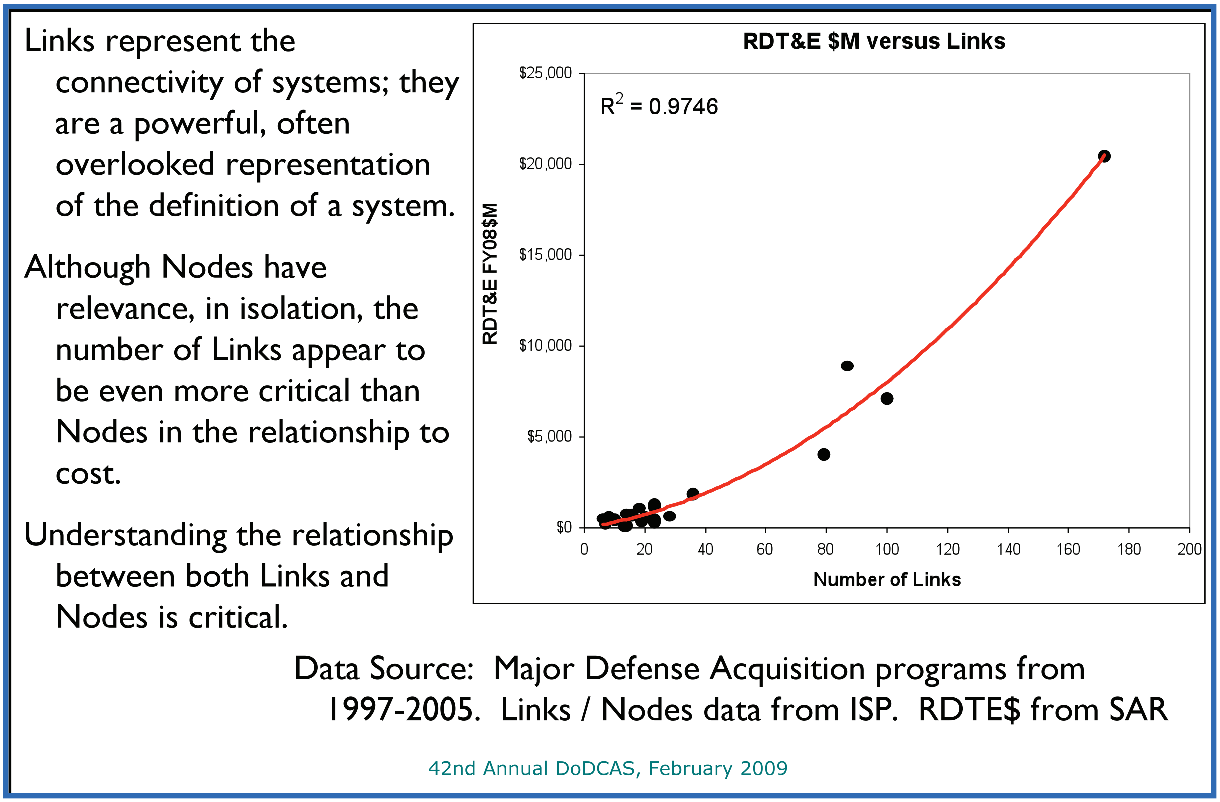

Figure 4 - Correlation of MDAP Interdependence with Development Resources