Addressing Emergence and Emergent Behavior in the Acquisition Lifecycle: How Are You Teaching, Planning, and Handling It?

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Abstract - *Understanding the complex emergent behavior of systems throughout the acquisition life cycle, especially those in the Department of Defense (DoD), is an under-addressed issue. For most, this will be a paradigm shift from traditional teaching, development, implementation, and sustainment of these systems. Since emergence and emergent behavior is unpredictable and often unrepeatable, knowing if the behavior was truly an emergent characteristic or a part of the system's functionality is often difficult to pinpoint. Researchers have cautioned against betraying emergence and/or emergent behavior as "magical". This belief is in part the result of overstating the importance, benefits, and results of other approaches such as artificial intelligence, data mining, knowledge management and the negative connotations that have been associated with them. It should be noted that not all emergence and emergent behavior is bad. There are instances, frequently, where the emergent behavior is actually better than the intentional system functionality. Emergence and emergent behavior is going to happen - plan for it as best you can. The objective of this paper is to look at how academia can start to better prepare systems engineers, program managers, users, etc., through teaching and training, to recognize and address emergent behavior in the acquisition lifecycle. This needs to start by understanding what emergence and emergent behavior is.*

Keywords: Emergence; Emergent Behavior; Complex Adaptive Systems; Acquisition Lifecycle.

1 Introduction

Complex Adaptive Systems (CAS), as defined by Dooley (Elliott & Kiel, 2004) and the working definition for this paper, is one that behaves/evolves according to three key principles: (1) the system's history is irreversible, (2) the system's future is often unpredictable; and (3) order – sequence in which events occur, is emergent as opposed to predetermined. CAS also exhibit complexity and have the ability to adapt over time.

Understanding the complex emergent behavior of systems throughout the acquisition life cycle, especially those in the Department of Defense (DoD), is an underdressed issue. As Figure 1 shows, the acquisition lifecycle is a very complex process with many phases, milestones, reviews, and deliverables. In addition, there are financial, contractual, planning, programming, budgeting, and execution components that must be addressed for any system being developed or sustained by the DoD. Although the process remains the same, each system development and implementation is slightly different than the previous one. For must systems engineers, it takes years to understand this lifecycle and effectively walkthrough it on a project.

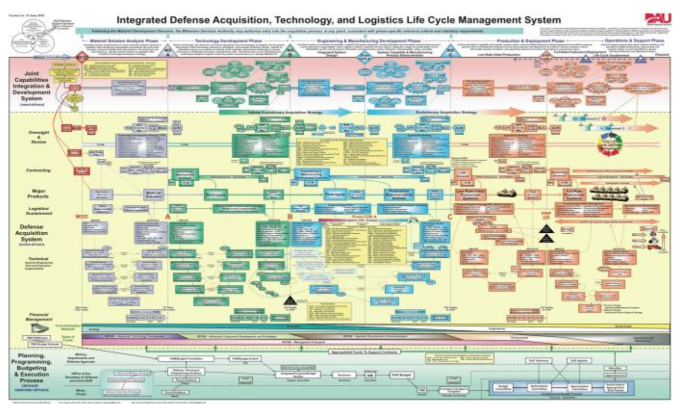

Figure 1: Integrated Defense Acquisition, Technology, and Logistics Lifecycle Management System

The importance of how people think, their thought processes, how they interact with each other (on a project as well as with their peers, colleagues, and supervisors) is often an underlying factor in determining system development success. Designing complex systems require more that technical expertise and brute force. Systems engineers should be able to look at the interrelationships not only of their area of expertise but those subsystems that make up the system. Critical thinking skills in the arsenal of a systems engineer are invaluable.

Research and advances in systems engineering are looking to address systems engineering from a more global perspective in contrast to breaking systems into smaller parts. Complex systems have shown that the system as a whole may be greater than the sum of its parts. Systems thinking looks to view the whole, not the sum of the parts, and how the parts are going to work once they have been put together.

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2 Beyond a Traditional Systems Engineering Approach

Traditional reductionism approaches break a problem into its smallest or simplest parts and attack the problem modularly. Complexity theory and complex systems, in contrast, does not break down the system but instead examines the system from a global perspective. This approach is taken because the systems' overall behavior or performance may be very different than those exhibited by the individual parts. This realization is also acknowledged in the International Council on Systems Engineering (INCOSE) Handbook (Haskins, 2011) by stating, "complexity can lead to unexpected and unpredictable behavior of systems; hence, one of the objectives is to minimize undesirable consequences."

Academia and the DoD can further acknowledge that not all systems engineering can and will take a traditional systems engineering solution. The systems engineering practitioners and community as a whole should be more educated as to when an alternative approach would need to be used. With that in mind, they can begin an earlier and stronger introduction at the undergraduate course-work levels.

Teaching non-traditional systems engineering has made it to the mainstream in academia or the DoD in the last couple of years. However, more and more institutions of higher learning are starting t0 recognize and understand the importance of teaching CAS and complexity at the undergraduate levels. This can be seen at Arizona State University (ASU) which offers many different alternative paths into CAS. The School of Human Evolution & Social Change has a Complex Adaptive Systems Science Concentration. Its School of Life Sciences offers a Ph.D. in Complex Adaptive Systems Science (CASS). The School of Sustainability offers a Complex Adaptive Systems Science Graduate Certificate. This is a vast increase from several years ago.

Some schools offer advanced courses, usually upper-level, where complex systems are introduced as a special topic. Missouri University of Science & Technology Systems Engineering Graduate Program hosts an annual CAS conference each years with some the industry and academic leaders in the field. There are other schools that have also established centers, centered large research programs, and offering advanced degrees in various areas of CASs.

Iowa State University offers an Interdepartmental Graduate Minor in CAS. Internationally, Chalmers University of Technology, located in Gothenburg, Sweden offers a masters in CAS. As recent as last year Stevens Institute of Technology launched its Center for Complex Systems and Enterprises with DoD industry charter members such as Lockheed Martin and Northern Light. In addition, other centers such as the New England Complex Systems Institute (NECSI) and Santa Fe Institute (SFI) are alternatives for research and hands-on experience.

If an alternative approach to systems engineering is not taught or introduced, one can assume those systems engineers may not be able to identify, address or relate to the deviations (emergence/emergent behavior) that occurs during the acquisition life cycle of complex systems. It is not being stated or implied that traditional systems engineering methodologies and approaches should be abandoned. However, as systems become more complex, development is becoming more complex, expensive, and time consuming.

One approach that could be taken is to make complexity, complexity theory, CAS, and the likes a required component of computer science and systems engineering curriculums. Examples of course work could include examples of everyday complex systems (e.g., internet, stock market, terrorism, etc.), projects and case studies for designing a complex system using either approach (pros and cons), and addressing unanticipated behavior and/or consequences once the systems have been fielded.

The Defense Acquisition University (DAU), a corporate university, provides training for the defense acquisition workforce. Training is both formal and online covering the areas of contracting, project management, logistics, as well as systems engineering. As part of that training, several systems engineering courses are taught that cover the spectrum of the fundamentals of systems planning, research, development, and engineering to technical leadership in systems engineering. However, none of the courses address complex systems, which many of the Defense systems built, deployed, and sustained are, whether they have been specifically identified as such.

One could make the leap that if it is not being taught or planned for how would it be recognized, and what would one actually be looking for? Being able to recognize, identify, and address unanticipated behavior in a system is not an easy task. Since emergence and emergent behavior is unpredictable and often unrepeatable, knowing if the behavior was truly an emergent characteristic or a part of the system's functionality. Knowing when and how to identify additional emergence and emergent behavior(s) requires education and training that most systems engineers have not been received.

3 What is Emergence/Emergent Behavior Anyway?

Emergence and/or emergent behavior seems to be more accepted in biological systems. The belief is that these systems have been studied for longer period of time and are more tangible, thus making observers feel it is more realistic. From a biological perspective, emergent behavior can be clearly seen in ant colonies, birds flocking, and insect swarming. As individuals, birds and insects do not display these behaviors. These behaviors only emerge when they are part of a group. These patterns and behavior are often unexplainable, non-repeatable, or duplicable. It should be noted that not all emergence and emergent behavior is bad. There are frequent instances where the emergent behavior is actually better than the intentional system functionality. Other example of emergence and emergent behavior can be found in the research of (Standish, 2001), (Lewin, 1998), and (Holland, 1997).

There are slightly different perspectives on emergence and emergent behavior depending upon the context of the domain area in which it is being described (e.g., biological systems vs computer/engineering systems). Several researchers have cautioned against betraying emergence and/or emergent behavior as "magical". This cautionary approach has been seen more in the computer and engineering literature than in the literature relating to biological systems. This belief this is the result of overstating the importance, benefits, and results of other approaches such as artificial intelligence, data mining, knowledge management, and the negative connotations that have been associated with them.

A good example of emergence in computer and engineering systems is the World Wide Web (WWW). The WWW has no central point of origin and is not regulated by any one entity, yet it functions through the use of pages. This behavior would not have been expected of a network of this nature. Another example of this behavior can be seen in the human body. The heart, lungs, and/or brain, etc. as individual parts of the body cannot perform on their own, however, they are essential for the sustainment of human life. No individual part, attempting to work alone, would or could perform the way the human body does as a whole. As noted in Rinaldi (2001), additional complexity exhibited by a system as a whole, beyond the simple sum of its parts, is called emergent behavior and is a trademark of CAS.

Heylighen, 1997) believes that despite being new and not yet very well established, CAS have been studied by some of the greatest scientific minds of the 20th century, including numerous Nobel Prize winners and other luminaries. Emergence and its importance, according to (Standish, 2001), stems from the belief that emergence is the key ingredient that makes a system a complex system. (Lewin, 1998) suggests that fundamental to CASs is the emergence of high-level order from low-level interactions among heterogeneous, autonomous agents, each guided by a few simple rules.

In 1997, Holland identified the following concepts of emergence:

- Emergence occurs in systems that are generated.
- The whole is more than the sum of the parts in the generated systems.
- Emergent phenomena in generated systems are, typically, persistent patterns with changing components.
- The context in which a persistent emergent pattern in embedded determines its function.
- Interactions between persistent patterns add constraints and checks that provide increasing "competence" as the number of such patterns increase.
- Persistent patterns often satisfy macrolaws.

(Rothfeder, 2004), defined Agent-based Modeling (ABM) as a "child of complexity theory, which holds that the organization of complex systems hinges on the interplay of seemingly haphazard individual events. Complicated patterns - how ants behave collectively, how terrorists choose targets - emerge from what appears to be randomness. Bottom-up analysis begins with the small events, the unseen interactions of agents that influence the whole system, and seeks to connect the local to, in political terms, the regional, national and international".

According to (Samuelson, 2005), the premises of ABM lies in simulation and system dynamics, made famous by Jay Forrester and others at MIT in the 1960's and 1970's. One of the primary focuses of ABM was to go beyond traditional simulation methods and incorporate behaviors that could be noted to change over time, depending upon what the circumstances were, noted in (Samuelson, 2005). ABM, (Bernard, 1999), uses a more aggressive method for predicting micro level interactions and changes then traditional simulations. These individual interactions may lead to a sum greater than the sum of the individual interactions.

As seen in (Rothfeder, 2004), the DoD became interested in ABM as an alternative to traditional war games, which are based on probability studies and statistical analysis and make no claim to understanding human thought. (Long & Mackey, 2003) observe that while intelligence analysis begins with intercepted or gathered raw data, it needs to evolve from this data the ability to generate predictions of possible/likely actions of the opponent. It is the opinion of (Anthes, 2003) that it is impossible to simulate this complex behavior by programming software agents with a few rules and letting them interact with each other. Anthes suggests that by optimizing the "agents" activities at the local level, it is possible to improve the performance of the system as a whole. Anthes also suggests that by optimizing the "agents" activities at the local level, it is possible to improve the performance of the system as a "whole". "Whole" is being defined as the agents working together in concert to achieve one goal. ABM, according to Anthes, can be used to help understand, predict emergent behaviors, and devise new rules for local agents that will improve the performance of the system as a whole. This opinion is shared by the author in that all rules or variables would not or could not be accounted for or predetermined at the beginning of development.

(Shimizu, 2002) notes that a global system consists of many local subsystems. Shimizu proposes that by specifying the dynamics of each subsystem and the local interaction between the subsystems, then the relationship between the dynamics of the global system and that of the local system, and kinds of new functions that appear in the global system, can be studied.

4 Conclusions

In Bar-Yam's latest 2004 work he took a look at how complex systems can be applied to everyday problems. Bar-Yam starts by looking at parts, wholes and relationships, complexity, and scale in organizations. He looks at real world entities such as healthcare, military warfare, education, global control, ethnic violence, and terrorism. Bar-Yam's practical examples make it easier to see and understand a problem area that is under addressed.

Emergence and emergent behavior is going to happen - plan for it as best you can. Exposure ad planning will entail educating much earlier in academia. Steps have been made in the early exposure of CAS as seen in recent undergraduate and graduate curriculums. To continue this progress and ensure its success, the DoD needs to embrace and re-enforce the exposure from the lower levels. This will also include revisions to its own curriculums and certification processes.

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