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"THE EVOLUTION OF C2"

Technical and Scientific Architecture For Testing and Evaluating Net-Centric Ecosystem

Suggested Topics: Experimentation and Analysis; Modeling and Simulation; C2 Architectures and Technologies

Name of Author: Kofi Nyamekye, PhD

Point of Contact: Kofi Nyamekye, PhD

Name of Organization: Integrated Activity-Based Simulation Research, Inc.

Complete Address: PO Box 421, Rolla MO 65402

Telephone: 573-202-8373

E-mail Address: kofinsoyameye@earthlink.net

ABSTRACT

Few publications exist that establish the technical and scientific architecture for designing, testing and evaluating the Net-Centric Ecosystem. Without a scientific foundation for testing and evaluating mixed-entities, individuals and systems in Net-Centric Environment, there is no scientific proof that such actors and systems would work when they are deployed in different mission scenarios. The National Research Council's report to the Army on Net-Centric Operations illustrates this issue:

"(t)he development of the Army's Future Combat Systems (FCS) is experiencing cost and schedule overruns because of the immense complexity of the effort (Weiner, 2005). Given the committee's findings about the immaturity of network science, this is hardly surprising. Designing and testing the FCS communications network alone is like trying to design and test a modern jet aircraft without the benefit of the science of aerodynamics or like designing and testing a radio or TV without the benefit of the fundamental knowledge of electromagnetic waves…

The engineering of complex physical networks, like that of the FCS, is not predictable because the scientific basis for constructing and evaluating such designs is immature." [National Research Council Report for the U.S. Army on "Net-Centric Operations, Pages 7 & 8, Introduction" 2005.]

This paper addresses such a need.

INTRODUCTION

Alberts et al. [Alberts et al. 1999] define Net-Centricity as follows:

"*Net-Centricity is an information superiority-enabled concept of operations that generates increased combat power by networking sensors, decision makers, and shooters to achieve shared awareness, increased speed of command, higher tempo of operations, greater lethality, increased survivability, and a degree of self-synchronization.*

In essence, (Net-Centricity) translates information superiority into combat power by effectively linking knowledgeable entities in the battlespace."

The implications of Net-Centricity for the 21st Century Warfare are that knowledgeable entities on the battlefield not only include commanders and warfighters on the battlefield but also they include our former adversaries, such as the Sunni tribal leaders and local tribesmen [Ricks 2006], who become our friendly allies (with human intelligence information), futuristic net-centric warfare platforms with cognitive capabilities (human intelligence capabilities) and other intelligent mixed-entities. Today military operations include not only combat operations but also civil operations such as humanitarian operations, peacekeeping operations, and so on. Designing, testing and evaluating the Net-Centric Ecosystem and more importantly evaluating the performance of the entities in an adaptive Net-Centric Environment, is extremely challenging. In fact, to date no technical and scientific architecture exist for testing and evaluating Net-Centric

Enterprise. The National Research Council's report [NRC 2005] to the Army, on Net-Centric Operations (NCO) and more importantly about the lack of any scientific basis for evaluating the FCS, attests to this missing gap. This paper addresses this critical missing gap. The organization of this paper is as follows. First, we will provide the literature review on any previously related work, for example the National Research Council on networks [NRC 2005]. We will then discuss *Power to the Edge* for the four domains of Net-Centric Ecosystem [Alberts et al. 2003]. Then we will emphasize that the *Power to the Edge* could not only be applied to the Design and Architecture of Systems, such as Net-Centric Enterprise, but also it could be applied to testing and evaluating large-scale systems-of-systems (SoS). Third, we will discuss the complexity theory as envisioned by Moffat, elaborating on the power-law function as a mathematical model to evaluate the performance of the warfighters that can achieve infinite adaptability in a dynamic battlefield environments [Moffat 2003]. Fourth, we will review International Test and Evaluation Association (ITEA) recent efforts on testing and evaluating Net-Centric enterprise, followed by Carley's [Carley 2005] work on organizational design and performance with emphasis on measurements of cognitive and social aspects of the workforce. Fifth, we will borrow from the author's previous work on Axiomatic Design [Nyamekye June 2007; Nyamekye June 2008; Nyamekye June 2009] as the technical and scientific foundation for large-scale SoS design and evaluation, followed by a discussion of a generic hypothetical technical and scientific architecture for designing, testing and evaluating the Net-Centric Ecosystem. Lastly, we will emphasize the new paradigm, which Nyamekye has recently envisioned for designing, testing, and evaluating the Net-Centric Ecosystem. Conclusions will then follow.

We must emphasize that while the paper focuses on ***test and evaluation***, we have occasionally used the phrase ***designing, testing and evaluation*** throughout the paper to point out that ***test and evaluation*** can only occur after a design phase. That is, we must always iterate between the "design" and "test and evaluation" to achieve a satisfactory product, systems, or systems-of-systems.

LITERATURE REVIEW

Despite much literature that exists on test and evaluation (T & E), very few publications appear on the technical and scientific architecture for testing and evaluating Net-Centric Ecosystem or complex large-scale systems-of-systems (SoS). In fact, extensive literature survey on technical and scientific architecture for test and evaluation (T & E) of Net-Centric Ecosystem has unearthed about one to two articles on this emerging discipline. Among them is the National Research Council (NRC) Report on Net-Centric Operations (NCO). Though the NRC did not specifically mention the term "test and evaluation," their report indirectly implies such a missing gap. They classified all complex large-scale SoS, for example the FCS, under a new scientific discipline known as "Network Science." According to NRC we know a lot about the design, construction, and use of the components of physical networks. However, the science of integrating these components into large, complex, interacting networks, for example the Global Information Grid (GIG), that are robust and whose behaviors are predictable is uncharted ground. For example, communications networks that are being built today exhibit unpredictable behavior and robustness. Without first testing and evaluating the individual components and retesting and reevaluating the integrated SoS when the networks of individual components interact with each, we cannot achieve robustness of such complex large-scale SoS. The NRC strongly emphasized that the development of predictive models of the behavior of large complex networks is difficult and without a strong scientific basis for constructing and evaluating such designs, achieving the tenets of Net-Centric Operations would be extremely difficult [NRC 2005].

Drawing on the Principles of *Power to the Edge* and Axiomatic Design, Nyamekye has recently discussed the importance of using the scientific concepts for testing and evaluating the Net-Centric Enterprise [Nyamekye June 2010]. He emphasized that we must first borrow from *Power to the Edge* concepts that say that we should first establish Architecture Design And Systems before we can proceed with Command and Control (C2) and more importantly, the Campaigns of Experimentation, which involves test and evaluation of complex endeavors [Alberts et al. 2007]. However, Nyamekye did not discuss any architecture, which establishes the scientific basis for designing, testing and evaluating any complex large-scale systems. Of particular importance is how we test and evaluate the cognitive and social behaviors of participants with diverse cultural backgrounds, typical in counterinsurgency operations and especially in humanitarian efforts during natural disasters. We should emphasize that the cognitive and social behaviors exist in cognitive and social domains in any enterprise, respectively. To understand the four domains and how they relate to the test and evaluation, a brief overview of applications of *Power to the Edge* is essential before subsequent discussions.

Alberts et al. have emphasized that we can apply the principles of the *Power to the Edge* in two ways across the four domains of any Net-Centric Enterprise [Alberts et al. 2003]:

- ❖ Design and architecture of systems-of-systems -- infostructure -- relate to the physical and information domains. The C2 sensors, systems-of-systems, platforms, and facilities exist in the physical domain. The information collected, posted, pulled, displayed, processed, and stored exists in the information domain.

- ❖ C2 (or organization and management of work) relates primarily to cognitive and social domains. The perceptions and understanding of what this information states and means exist in the cognitive domain. Also in the cognitive domain are the mental models, preconceptions, biases, and values that serve to influence how information is interpreted and understood, as well as the nature of the responses that may be considered. Interactions between and among individuals and entities that fundamentally define organization and doctrine exist in the social domain.

Though test and evaluation are not directly mentioned in the *Power to the Edge*, it is quite clear from Alberts et al.'s work [Alberts et al. 2003] that we must address these domains when designing, testing and evaluating each component. For example, a futuristic net-centric platform, which operates in a futuristic DoD Edge-Based Organization, must not only be tested and evaluated as an autonomous unit in the physical and information domains but also it must be tested and evaluated in actual interactions with other components in the social domain in a Net-Centric Ecosystem, to achieve the global behavior of a given mission. When we test and evaluate the perceptions and understandings of individuals as autonomous units, we are essentially doing so in the cognitive domain. Thus, any technical and scientific architecture for test and evaluation should embody the principles of the *Power to the Edge*. To reinforce this thinking, Garstka et al.

[Garstka et al. June 2004] have created the Net-Centric Operations Conceptual Framework (NCO-CF), Figure 1, for not only educating researchers about NCO tenets but also for helping researchers organize their work and apply comparable metrics to design test and evaluate any research efforts across all the domains as previously noted. A brief overview of Figure 1 is essential. Figure 2 is essential in understanding Figure 1.

Each concept, for example, "Degree of Networking" in the top-level concepts (Figure 1) designated as the "top-level concepts" (Figure 2), is described by a set of attributes and metrics (at the second level, Figure 2), which we need to consider before any test and evaluation. The attributes measure characteristics of the concept in terms of quantity (how much? how often? how long?) and quality (how correct? how appropriate? how complete?). Each attribute is actually measured by a metric (or set of metrics) that specifies in detail what data would be needed to measure the attribute. For instance, the "Degree of Networking" is comprised of net-ready nodes and the network.

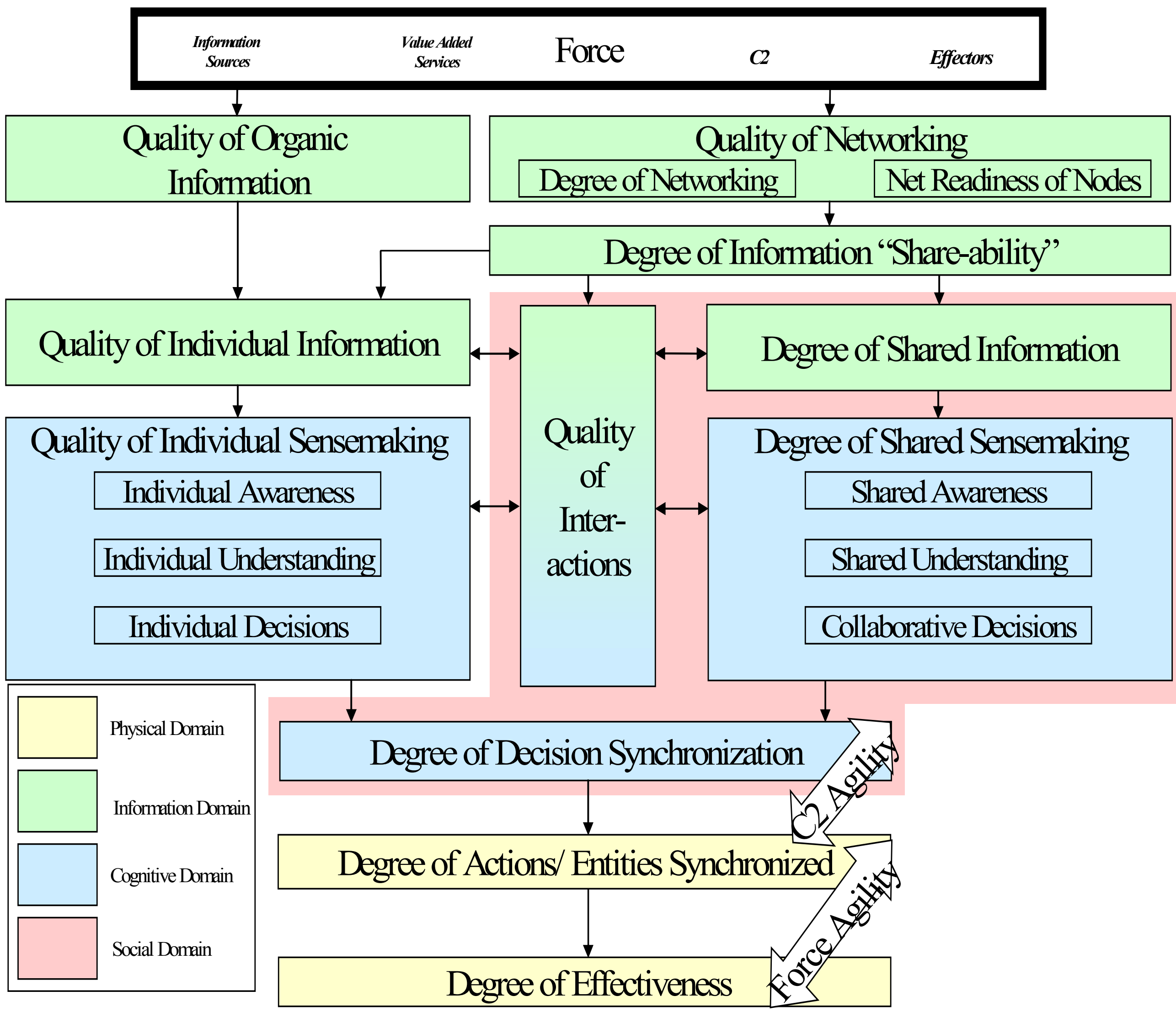

Figure 1. The Net-Centric Conceptual Framework [Garstka et al. June 2004.]

In order to evaluate the impact of various levels and qualities of networking on force performance and outcomes, it is necessary to measure these levels and qualities, in testing and evaluating a Net-Centric Ecosystem. For example, as Figure 2 illustrates, the attributes of net ready nodes are: Capacity, Connectivity, Post and Retrieve Capability Support, Collaboration Support, and Node Assurance. The attributes of the network are: Reach, Quality of Service, Network Assurance, and Network Agility. In order to gather data to assess each of these attributes, specific metrics are needed. The Conceptual Framework provides metrics for each attribute. For example, Network Reach can be measured by the percentage of nodes that can communicate in desired access modes, information formats, and applications.

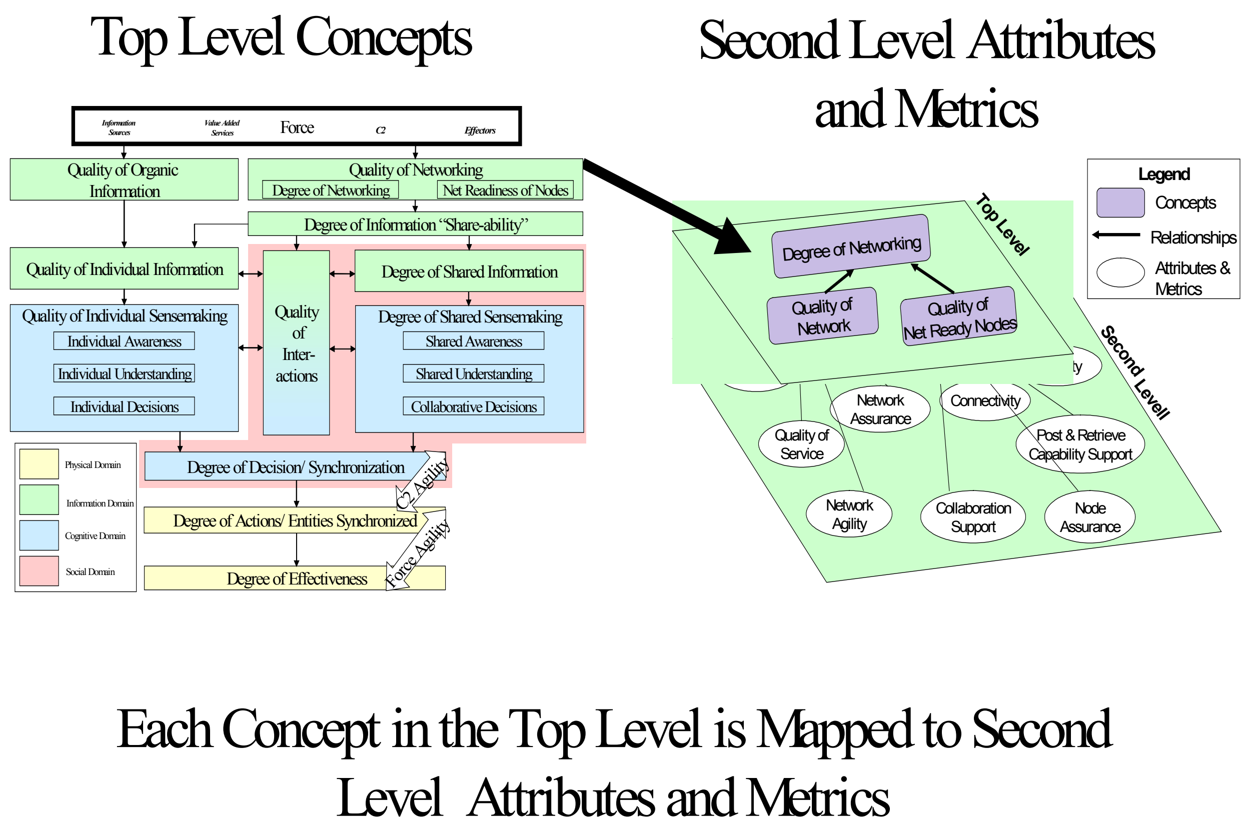

Figure 2. The Net-Centric Conceptual Framework Top Level and Second Level View [Alberts et al. June 2004.]

Moffat discussed experimental mathematics as a way to analyze the co-evolution of complex adaptive systems, such as the DoD Net-Centric Enterprise and its supporting infostructure -- GIG [Moffat 2003]. He considered an ecosystem consisting of a large number of interacting species (such as the force elements at the grid points in GIG), each evolving in response to the environment created by the rest of the ecosystem (that is, each species is *coevolving*) [Moffat 2003]. Such a system consists of many components that interact through some kind of exchange of forces or information [Moffat 2003]. In addition to the internal interactions, some external force -- natural selection -- may drive the system in this case. The system will now evolve over time under the influence of the external driving forces and the internal interactions. The questions Moffat was trying to answer were as follows. *What happens when we observe such a system* [Moffat 2003]? *Is there some simplifying mechanism that produces a typical behavior shared by large classes of such systems* [Moffat 2003]? He established that *clustering* was the mechanism. He found that as the species interact, they co-evolve into clusters and when the cluster size reaches a critical value or natural fitness value, the system would have optimal flexibility. That is, clusters of all sizes can be created. The physical implication is that the ecosystem can achieve infinite agility, which is one of the major requirements of the force structure for Net-Centric Warfare (NCW) and more importantly futuristic Net-Centric platforms for counterinsurgency operations. Furthermore, at the critical fitness value, the species interact to achieve the global behavior of the entire ecosystem. More importantly, he established that we could use the power-law function (or exponential density function) to ***evaluate the performance*** of such a force structure. Despite his visionary work, he did not explain how we could adapt it to design, test and evaluate the Net-Centric Enterprise, for example how we design, test and evaluate the GIG network to adapt itself to uncertainties such as cyber attack, on the battlefield. Axiomatic Design fulfills the deficiencies of Moffat's work.

Recently, the International Test and Evaluation Association (ITEA), has designed workshops for educational training in Net-Centricity. The workshop on End-to-End Testing in a Net-Centric Environment, which ITEA held on November 2-5, in San Diego, attests to this [http://www.itea.org/files/2009/2009%200139%20End%20to%20End%20FINAL%20brochure.pdf].

- Testing in Service Oriented Architectures (SOA)
- Sensor to shooter testing
- The use of modeling and simulation in network centric testing
- The implications for testing against cyber threats.

While ITEA's efforts are important, especially the emphasis on SOA concept, which is essential for constructing, testing and evaluating large-scale complex SoS, ITEA's efforts still lack technical and scientific rigor, as the NRC previously noted.

Carley, at Carnegie Mellon University (CMU), has done much work in organizational design as a way of testing and evaluating the cognitive and social beliefs of agents in a Net-Centric Environment [Carley 2005]. She modeled an organization as a set of interlocked networks connecting entities such as people, knowledge resources, tasks and groups. We can represent these interlocked networks using meta-matrix conceptual framework, Table 1. Carley defined meta-matrix as a conceptual description of an organization and as an ontology for characterizing key organizational entities and the relations among them. She designed a scientific research tool known as Organization Risk Analyzer (ORA) to test and evaluate the performance of agents in an organization. She established several metrics for evaluating the performance of the agents. Among the metrics is cognitive demand, which measures the total amount of cognitive effort expended by each agent to its tasks. Her work is very intriguing because we can use it to measure the cognitive demand of warfighters on the battlefield. The results could then help the commanders and the warfighters on the battlefield to determine the effect of such a metric and other metrics on the success or failure of mission outcomes and the remedial actions to ensure a mission success, before actual execution of combat operations. More importantly, if we can build a hybrid-model consisting of Carley's work, agent-based modeling and simulation (ABMS), and Service Oriented-Architecture (SOA)-Based Cloud Computing Model [Nyamekye June 2010], we can achieve a promising future to designing a technical and scientific architecture for testing and evaluating Net-Centric Ecosystem. For details on SOA-Based Cloud Computing Model, please refer to the recent work of Nyamekye [Nyamekye June 2010]. To achieve such a vision, we need a technical and scientific basis such as Axiomatic Design, pioneered by Suh at Massachusetts Institute of Technology, to establish such architecture [Suh 1990; Suh 2001]. A brief overview of the design loop proposed by Wilson as the framework for discussing Axiomatic Design is essential. Suh, the architect of Axiomatic Design, previously used Wilson's framework [Wilson 1980].

	People	Knowledge	Resources	Tasks/Projects
People	Social Network *Who talks to, works with, and reports to whom*	Knowledge Network *Who knows what, has what expertise or skills*	Resource Network *Who has access to or can use which resource*	Assignment Network *Who is assigned to which task or project, who does what*
Knowledge		Information Network *Connections among types of knowledge, mental models*	Resource Usage Requirements *What type of knowledge is needed to use that resource*	Knowledge Requirements *What type of knowledge is needed for that task or project*
Resources			Inter-operability and Co-usage Requirements *Connections among resources, substitutions*	Resource Requirements *What type of resources are needed for that task or project*
Tasks/ Projects				Precedence and Dependencies *Which tasks are related to which*

Table 1. Meta-Matrix Showing Networks of Relations Connecting Node Entities [Carley 2005.]

According to Wilson, a design process begins with the establishment of the *functional requirements* (FRs) to fulfill a given set of needs. The design then ends with the creation of an entity (a product, a system, systems-of-systems, or a process) that fulfils the *functional requirements*. Figure 3 shows the design process. The design process begins with the recognition of the *societal need*. Typically, the *societal need* is usually unclear. For example, the U.S. Army's need may be to achieve Information Age Transformation [TRADOC], but it may not be clear with the details of such a need, for example, the need for scientific research programs such as the Network Science required [NRC 2005] for achieving it. The need is then coded into a concrete *set of functional requirements*. In the Information Age Transformation, a *specific functional requirement* in the *set of functional requirements* may be -- "Create an adaptive robust Net-Centric Value Systems to support high-tempo of operations in any battlefield, including asymmetric warfare

." Please note that the *functional requirements* could be specified for any domain, for example "executive a mission task" occurs in the physical domain. After the need is coded, ideas are generated to create the product or system. In the Information Age Transformation example, the final system may be -- "Future Combat Systems (FCS)." The product, systems, or systems-of-systems is ***tested and evaluated*** and the performance measures compared with the original *set of functional requirements* through a feedback loop. When the product, systems, or systems-of-systems does not fully satisfy the original *set of functional requirements*, then we must reformulate new ideas or change the *functional requirements* to be accurately consistent with the *societal need*. We continue this iteration until we create an acceptable system. The final product or system is tested in the marketplace or on the battlefield.

We should emphasize that when the *societal need* changes, the product or system may not be adequate to meet the new need. Consequently, we must go through the design loop again to redesign the existing product or system or completely design a new product or system.

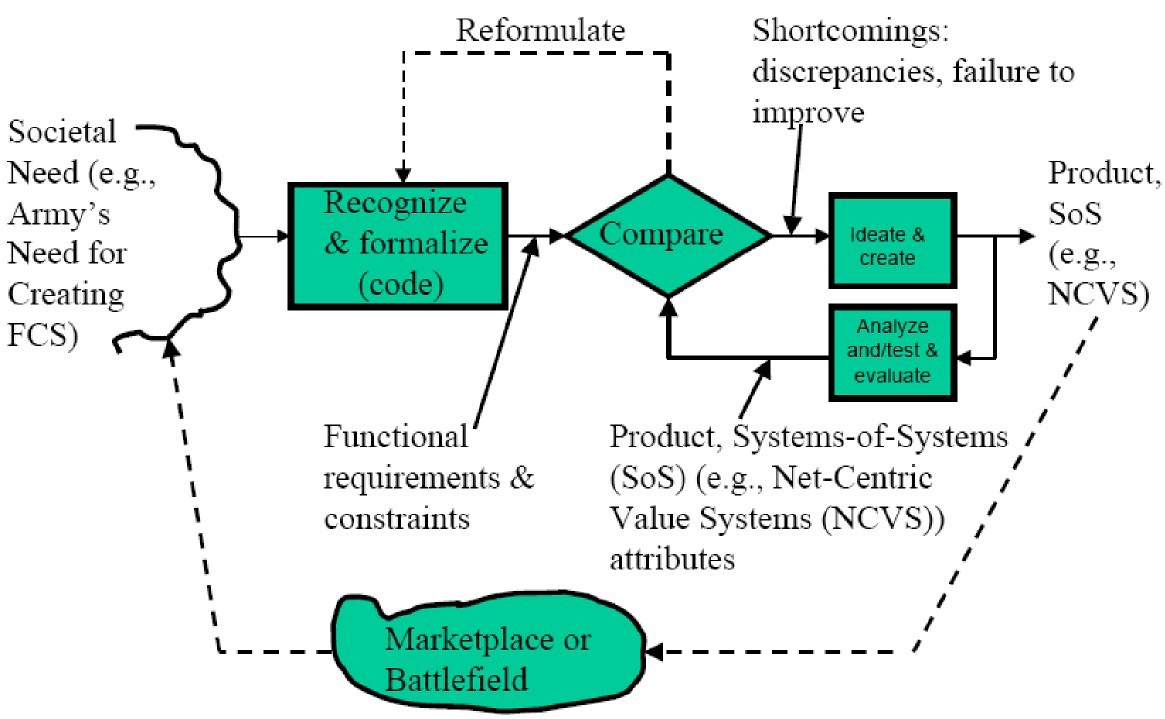

Figure 3. The Design Loop-As the Architecture for Systems-of-Systems [Nyamekye 2007; Wilson, D. R., Ph.D. Thesis, MIT, August, 1980]

Recognizing that for centuries design has been treated as an art, the National Science Foundation (NSF) funded a research program at the Massachusetts Institute of Technology (MIT) in the early 1980s to establish the scientific basis for design [Suh 1990].

Under a major grant from NSF, Suh and his coworkers conducted a major research program that led to the establishment of Axiomatic Design theory [Suh 1990]. According to Suh, "design involves a continuous interplay between what we want to achieve and how we want to achieve it." What we want to achieve is the goal of our design, and how we want to achieve it is our physical solution, Figure 4. Suh further explains that we must state the goals of a design in the functional domain or functional space, and generate the physical solution in the physical domain or physical space, Figure 4. The design procedure then involves interlinking these two domains at every hierarchical level of the design process. The two domains are independent of each other. What relates these two domains is the design.

To begin any design, we must determine the design's objectives by defining it in terms of specific requirements, called the functional requirements (FRs). Then, to satisfy these functional requirements, we must create the design solution in terms of design parameters (DPs). The design process involves relating these FRs of the functional domain to the DPs of the physical domain, Figure 4.

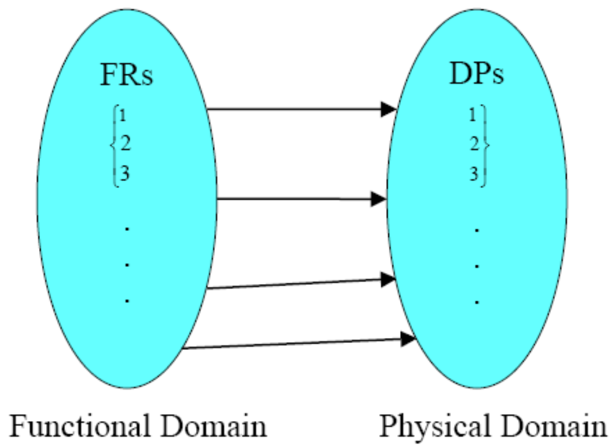

Figure 4. Mapping from the Functional Domain (or Space) to the Physical Domain [Nyamekye 2007; Suh 1990.]

Suh established two fundamental axioms that form the scientific basis of the axiomatic approach to design. They are:

AXIOM 1: In a good design, the independence of functional requirements (FRs) is maintained.

AXIOM 2: The design that has the minimum information content is the optimal design.

AXIOM 1 simply states that in designing any system, we must meet the goals (strategic or tactical requirements) of the system independently. For example, suppose the goals of designing an information visualization system are: 1) maximize the information benefits per unit cost and 2) minimize the total operational cost. According to AXIOM 1, the final design must satisfy both goals independently. Meeting the first goal should not affect the second goal. AXIOM 2 says that among the different designs that will meet both goals, the design that will require the least amount of information to describe it or will achieve the highest reliability of the system will be the best design. AXIOM 2 establishes the scientific foundation for an optimum design, ***through test and evaluation (T & E)***, of a product, process or a system, for example software, organization and so on. We should note that classical optimization models, from operation research field, do not generally yield optimum results when more than one criterion for which the system must be optimized, exist [Nakazawa and Suh 1984]. For example, when the goals of designing logistics system are both maximizing customer Service and minimizing the distribution costs, classical optimization models do not achieve optimum results. Consequently, axiomatic approach is superior to the traditional optimization techniques when the design must meet more than one goal, concurrently [Nakazawa and Suh 1984; Nakazawa 2001]. Furthermore, we can use Axiomatic Design to evaluate an existing design for improvements.

In addition to the functional requirements, a set of constraints may also exist. Constraints are factors that establish the boundary on acceptable design solutions. For example, some designers treat cost as a constraint. On the battlefield, how much collateral damage, and how many casualties are "acceptable" in a theater operation, could represent the constraints [Alberts et al. 2003]. Constraints are very similar to functional requirements in character and attributes except that the independence of constraints is not required in a good design.

In addition to AXIOMS 1 and 2, Suh has established corollaries and theorems for design. Among the corollaries and theorems derived from AXIOM 1 and AXIOM 2, the following four corollaries and two theorems, are essential for designing any large-scale systems-of-systems, namely [Suh 1990; Suh 2001; Nyamekye June 2008; Nyamekye June 2009]:

Corollary 1: Decoupling of Coupled Design: Decouple or separate parts or aspects of a solution if FRs are coupled or become interdependent in the proposed designs.

Corollary 2: Minimization of FRs: Minimize the number of functional requirements and constraints. Strive for maximum simplicity in overall design or the utmost simplicity in physical and functional characteristics.

Corollary 3: Integration of Physical Parts: Integrate design features into a single physical process, device, or system when FRs can be independently satisfied in the proposed solution.

Corollary 4: Use of Standardization: Use standardized or interchangeable parts, architecture, process, device, scientific concept, or system if the use of these parts, architecture, process, device, scientific concept, or system is consistent with the FRs and constraints.

THEOREM M2 (Large System with Several Subunits) When a large (e.g., organization) consists of several subunits, each unit must satisfy independent subsets of FRs so as to eliminate the possibility of creating a resource-intensive system or a coupled design for the entire system.

THEOREM S7 (Infinite Adaptability versus Completeness) A large flexible system with infinite (adaptability) may not represent the best design when the large system is used in a situation in which the complete set of FRs that the system must satisfy is known in priori.

For further details, please refer to the previous and recent work of Nyamekye [Nyamekye 2008; Nyamekye 2009] and Suh [Suh 1990; Suh 2001]. We should emphasize that *THEOREM S7* establishes the scientific base for designing a SoS with infinite agility, as espoused by Moffat [Moffat 2003]. Consequently, Axiomatic Design establishes the technical and scientific base for designing architecture for ***test and evaluation of Net-Centric Ecosystem***. In the subsequent sections we will borrow from the recent work of Nyamekye on Missions and Means Framework (MMF) [Nyamekye June 2009] as the technical foundation for the test and evaluation.

HYPOTHETICAL ARCHITECTURE

Nyamekye has recently noted that we can use Missions and Means Framework model for not only planning and execution of a DoD mission but also we can use it for ***designing, testing and evaluating*** the Net-Centric Ecosystem. We will discuss this new thinking later. A brief overview of the MMF follows.

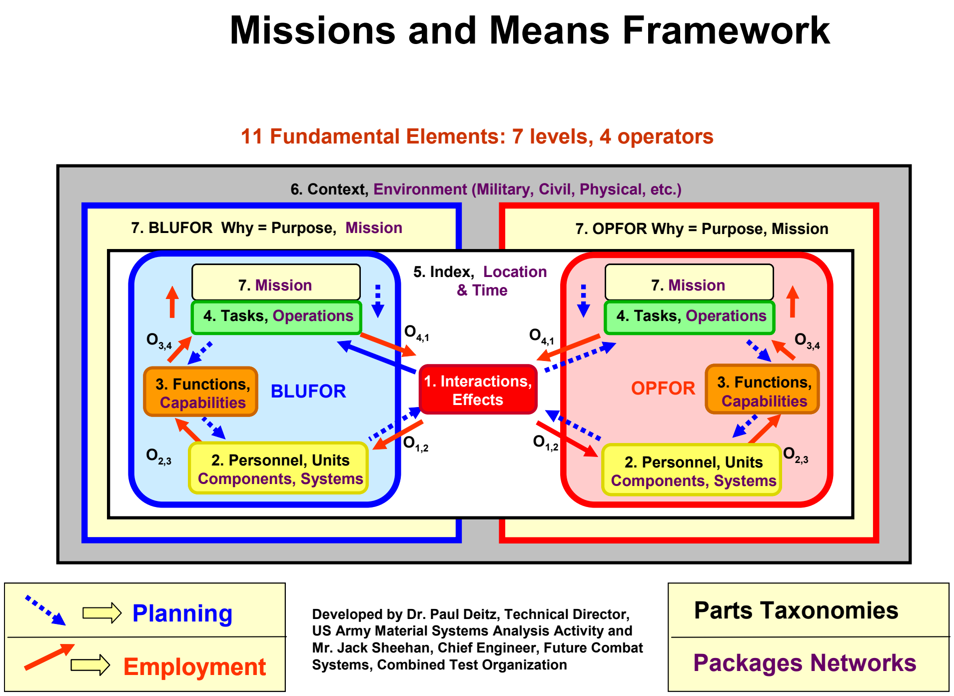

Figure 4. The Missions and Means Framework [Deitz et al. 2003.]

According to Deitz et al. [Deitz et al. 2003], the MMF Model begins with the creation of two fundamental entities at each of the seven levels of the framework as shown in Figure 4. Levels 5 through 7 characterize the *mission* portion of the MMF, while Levels 1 through 4 are considered the *means* portion of the framework [Watkins et al.]. Here the term *"means"* include <u>all resources and actions</u> taken in pursuit of the *missions* and their objectives. For example, the units or components tasked, how they are organized, and the strategies, operations, and task decomposition decisions are all considered part of the *means* to achieve the ends associated with the *mission*. At each echelon in a task-organized chain of command, the commander at that echelon works with some factors that are externally imposed and others that are at the commander's discretion. According to Deitz et al., Level 7 (Purpose, Mission), Level 6 (Context, Environment), and Level 5 (Index, Location/Time) represent the externally imposed factors by the central commander. These levels represent the static factors that are outside the span of control of the commander at that echelon. The own forces: Level 1 (Interactions, Effects), Level 2 (Components, Forces), Level 3 (Functions, Capabilities), Level 4 (Tasks, Operations) (and supporting operators) are considered dynamic and under the span of control of the own force commander at that echelon. The same is true with opposing force commander [Watkins et al.]. In addition to the levels described above, the MMF includes the following four *transformational operators*, which capture the dynamic relationships that exist between levels [Watkins et al.]: $\mathbf{O_{1,2}x}$ transforms Level-1 interaction specifications into Level-2 component states; $\mathbf{O_{2,3}x}$ transforms Level-2 component states into Level-3 functional performance; $\mathbf{O_{3,4}x}$ transforms Level-3 functional performance into Level-4 task effectiveness; and $\mathbf{O_{4,1}x}$ transforms Level-4 task effectiveness into Level-1 interaction conditions. The "**x**" postscript in each of the designations above refers to the "**S**" or "**E**" operator.

The MMF has two distinct versions of each *transformational operator*. Synthesis (S-suffix) is the top-down planning (blue arrows in Figure 4) and decision-making process that the warfighters use to create, define, and design a military evolution to meet mission requirements [Watkins et al.]. Employment (E-suffix) is the bottom-up execution (red arrows in Figure 4) and adjudication (red arrows in Figure 4) of actual outcomes when own and opposing missions/means collide in the battlespace [Watkins et al.]. Synthesis and Employment operators are not mathematical inverses. Obviously, the processes and procedures used to design a course of action are not the same as those used to execute it [Deitz et al. 2003].

Borrowing from Axiomatic Design we can create the complexity equations, in the form of design structure matrix [Suh 2001; Nyamekye June 2007], for the MMF. Below are the basic mathematical equations, from AXIOM 1 and Theorem S7. The basic Equations for FR_1 can be expressed as follows.

$$FR_1 \ \$ \ (DP^a{}_1, DP^b{}_1, DP^c{}_1 \ldots\ldots DP^r{}_1) \qquad \text{Equation 1}$$

Similarly, the equations for other FR_s can be structured as follows:

$$FR_2 \ \$ \ (DP^a{}_2, DP^b{}_2, DP^c{}_2 \ldots\ldots DP^q{}_2)$$

$$FR_3 \ \$ \ (DP^a{}_3, DP^b{}_3, DP^c{}_3 \ldots\ldots DP^w{}_3)$$

….

$$FR_m \ \$ \ (DP^a{}_m, DP^b{}_m, DP^c{}_m \ldots\ldots DP^s{}_m) \qquad \text{Equation 2}$$

Equation 1 simply states that FR_1, for example a mission task, can be satisfied (indicated by $) by selecting $DP^a{}_1$, $DP^b{}_1$, $DP^c{}_1$, etc. The $DP^a{}_1$ can represent for example, "Operations Package 1," from the knowledge base. Similarly, FR_m, satisfied by selecting $DP^a{}_m$, $DP^b{}_m$, etc. The $DP^a{}_m$, can represent for example, "Capability Package m", from the knowledge base. Please note that we can use Equations 1 and 2 to construct the knowledge base. We can employ Web Ontology Language (OWL) and Compendium [Nyamekye June 2009] to build the knowledge base. More importantly, Compendium supports OWL. In fact, OWL has been successfully used to construct a knowledge base in Compendium [Compendium]. Compendium is an emerging open source research and development system for creating knowledge base systems that address semantic interoperability issues in complex systems [Compendium]. Employing Nyamekye's previous work on partitioning model [Nyamekye June 2007] for grouping the DoD business tasks (from the DoD business processes) into clusters for creating SOA-Based C4ISR Ecosystems, we can construct for example "Operations Packages". In SOA, we can think of "Operations Package" as a "Service Package". Matching the appropriate "Force Package" to support appropriate corresponding "Capability Package" for executing the appropriate "Operations Package", we can create complex large-scale SoS or a "Net-Centric Ecosystem", to achieve an overall mission outcome. For details, please see Nyamekye's previous publications [Nyamekye June 2007; Nyamekye June 2008; Nyamekye 2009].

Using the Design Navigation Method or AXIOM 2, Carley's work, ABMS we can construct simulation models to test the performance of the Net-Centric Ecosystem. A brief overview of the Design Navigation Method is essential.

Nakazawa [Nakazawa 2001] has nicely discussed the approach for evaluating the total minimum information content (AXIOM 2) for several functional requirements, FRs, for example, tasks to execute the battlefield plans, or planning time. He calls the overall design concept, Design Navigation Method. For convenience, we will use the symbols from his work. The steps are as follows.

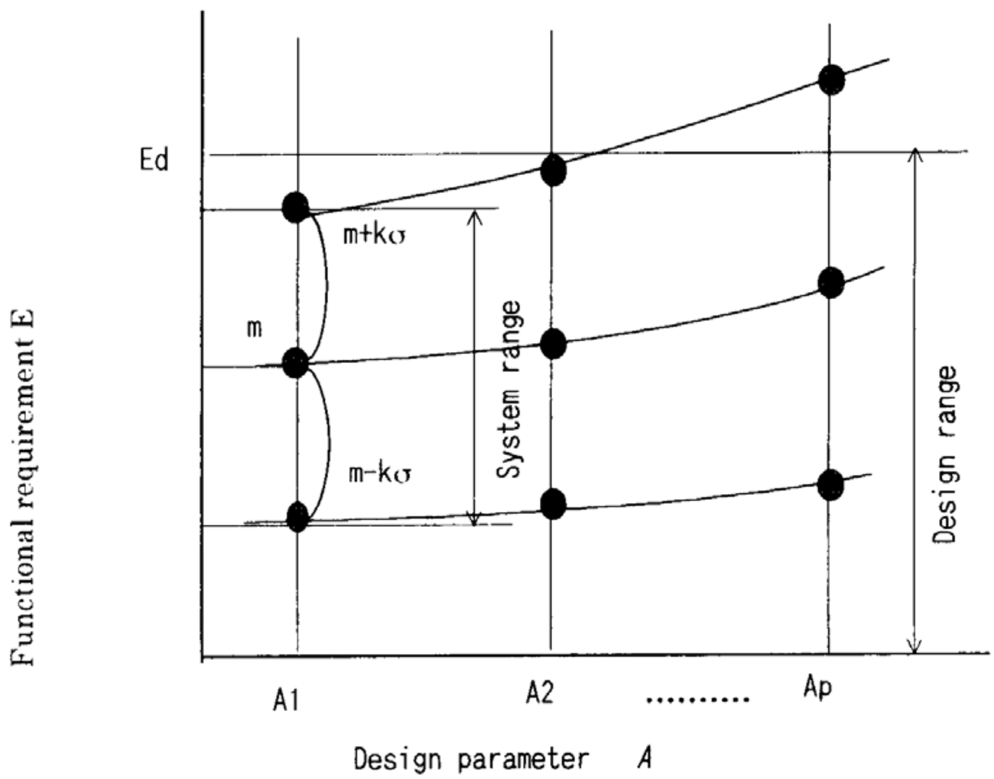

Figure 5. System Range of Design Parameter A for Functional Requirement [Nakazawa 2001.]

In Figure 5, the $A1, A2, ...Ap$ represent the different levels of a design parameter, DP (such as environmental factors, weather conditions), and the E represents the functional requirement, FR. Please note that the functional requirements (FRs) correspond to the measures- of-performance (MoPs) or measures-of-effectiveness (MoEs)--to evaluate the different plans [Alberts et al.

2007]--and the design parameters (DPs) correspond to the variables or elements that we can vary to achieve FRs. First we vary the design parameters to take on the values, $A1, A2, ...Ap$, each of which yields multiple (n) experimental or simulation data, on a given FR, or E. These data will show a scattered distribution. For the (n) data points gathered for $A1$, the mean, m, and the standard deviation σ (square root of unbiased variance) are obtained. The two points, representing $m \pm k\sigma$, are then plotted above $A1$, as we can see in Figure 5. The k is the safety factor. The two points will correspond to the upper and lower limits of the system range, for example the performance range of the Quality of Command [Alberts et al. 2007]. We then repeat the same method for the upper and lower limits for the rest of the parameter values, $A2$, ..., Ap. We then fit a line, a quadratic, or other curve through the points representing the upper limits, while those in the lower limits are fitted with another curve. We can now enter the design range (the range of a performance measure, such as the range of acceptable planning time established by the central commander), Ed for the upper value and the lower value, on the same graph, as we can see in Figure 5. We can now establish the common range (the overlap of design range with system range) for any design parameter value between $A1$ and Ap. Using the minimum information content model [Nyamekye June 2008], we find the information content (function error) for each design parameter value, between $A1$ and Ap. For example, at $A1$, we find the information content (function error). Similarly, we obtain the information content (function error) for $A2$ and Ap, respectively. We go through the entire steps again for the other functional requirements, for example Plan Quality [Alberts et al. 2007], and sum up the information contents (function errors) at each parameter value; plot the information content (function error) values as a function of the design parameter values on a graph, to obtain the total information content (total function error) curve. Figure 6 exhibits the total information content (total function error) curve.

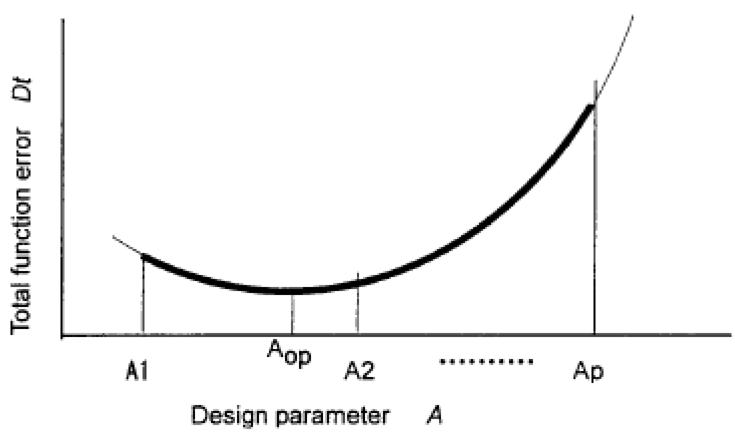

Figure 6. Total Information Content (Function Error Curve) [Nakazawa 2001.]

Please note that the total minimum information content (total function error) value occurs at Aop. However, within $A1$ and Ap, the total minimum information content (total function error) is acceptable, an approach which Alberts et al. [Alberts et al. 2003] has suggested for evaluating Net-Centric Warfare Model, due to uncertainties on the battlefield. Table 2 shows the experimental design for testing a hypothetical Net-Centric Ecosystem.

Nakazawa has shown such steps for many design parameters (especially when the design parameters exhibit interaction effects as in typical experimental designs) and many functional requirements. For convenience, we will omit the details of the discussion. Nyamekye has also recently used it to for evaluating network design for Command, Control, Communications, Computers, Intelligence, and Reconnaissance (C4ISR) SoS [Nyamekye June 2008] info-structure.

NO	DESIGN PARAMETERS (DPs)				EXPERIMENTAL OR SIMULATION RESULTS FOR FUNCTIONAL REQUIREMENTS (FRs)		
	A	B	C	D	E	F	G
1	A1	B1	C1	D1	E1	F1	G1
2	A1	B2	C2	D2	E2	F2	G2
3	A1	B3	C3	D3	E3	F3	G3
4	A2	B1	C1	D1	E1	F1	G1
5	A2	B2	C2	D2	E2	F2	G2
6	A2	B3	C3	D3	E3	F3	G3
7	A3	B1	C1	D1	E1	F1	G1
8	A3	B2	C2	D2	E2	F2	G2
9	A3	B3	C3	D3	E3	F3	G3

Table 2. Orthogonal Table For Experimental Design for Evaluating a Hypothetical Net-Centric Ecosystem -- AXIOM 2 [Nakazawa 2001.] The functional requirements (FRs) correspond to the measures-of-merit (MoPs) or measures-of-effectiveness (MoEs).

Figure 7 shows the hypothetical technical and scientific architecture for the ***testing and evaluating*** Net-Centric Ecosystem in a real-time distributed collaborative environment. Please notice that "ORA Engine" appears as one of the hybrid models. Axiomatic Design Engine ("AD Engine") constructs the MMF Model. The "AD Engine" also includes the Design Navigation Model for ***testing and evaluating*** the entire Net-Centric Ecosystem. A brief overview of Figure 7 is essential.

The "AD Engine" initially constructs the MMF model, which is a model of the Net-Centric Ecosystem (NCE). The "Intelligent Multi Media UDDI Business Registry I" stores the NCE model. Each UDDI registry represents the knowledge base, as we noted before. This "Intelligent Multi Media UDDI Business Registry" publishes to all other UDDI registries that an MMF model exists, and explains the details of appropriate packages with data for "ABMS Engine" and "ORA Engine". The "ORA Engine" creates a preliminary model of the entire ecosystem and stores the results in the "Intelligent Multi Media UDDI Business Registry M". This registry publishes the test and evaluation results. Please note that the “ORA Engine” has its own test and evaluation model. Each “ABMS Engine” examines the initial ORA’s results. Based on ORA’s preliminary results, each “ABMS Engine” conducts its simulation runs and stores the test results in its corresponding UDDI registry. The ABMS registries publish the test data to the UDDI registry for the “AD Engine”, which in turn uses the Design Navigation Method for creating the minimum information content curve, Figure 6, using AXIOM 2. From Figure 6, we can evaluate whether we have the correct force package (Level-2), which includes the network, appropriate warfighter skills and so on, to perform the functions (Level-3) to execute the tasks (Level-4) to achieve the desired mission outcomes (Level-7), in Figure 4.

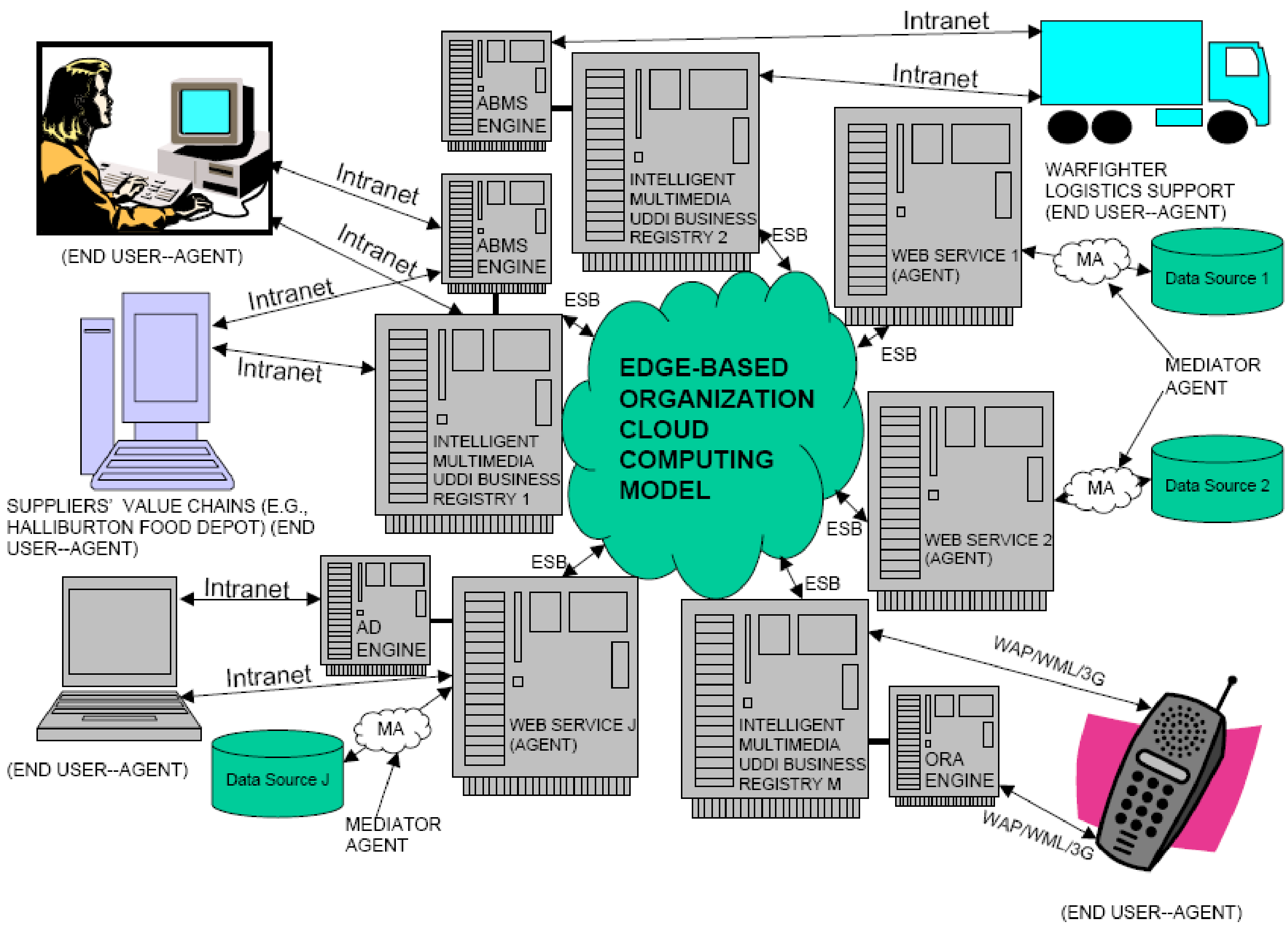

Figure 7. Hypothetical Technical And Scientific Architecture For Testing And Evaluating Net-Centric Ecosystem in Real-Time Distributed Collaborative Environment -- An updated version of Nyamekye’s previous work for SOA-Based Architecture for C4ISR SoS [Nyamekye June 2008.]
Legend: ABMS = Agent-Based Modeling and Simulation; ORA = Organization Risk Analyzer; UDDI = Universal Description, Discovery and Integration The Universal Description, Discovery and Integration); ESB = An Enterprise Service Bus [e.g., FCS Systems-of-Systems Common Operating Environment (SoSCOE)] -- Corollaries 3 and 1.

THE NEW PARADIGM FOR DESIGNING, TESTING AND EVALUATING THE NET-CENTRIC ECOSYSTEM

As noted before, Nyamekye has recently envisioned that we can use the Missions and Means Framework model for not only planning and executing a DoD mission but also we can use it for ***designing, testing and evaluating*** the Net-Centric Ecosystem. In fact, he has postulated this simple relationship for such an endeavor:

NET-CENTRIC ECOSYSTEM = MMF + AXIOMATIC DESIGN + ABMS + T & E

The implication of Nyamekye's thinking is that since Axiomatic Design can model the MMF, we can use it to first construct the Net-Centric Ecosystem -- AXIOM 1. Then we can use agent-based modeling and simulation (ABMS) to create a simulation model for interaction among the entities and the warfighters on the battlefield using an experimental design to construct the simulation test. From the simulation test results, we can use the appropriate measures of performance (MoPs) or measures of effectiveness (MoEs) to evaluate the performance of the entire Net-Centric Ecosystem -- AXIOM 2. In fact, the Design Navigation Method [Nakazawa 2001; Nyamekye 2010], an extension of Axiomatic Design, exemplifies Nyamekye's new thinking. This issue is very intriguing. It means that we can use this new technical and scientific thinking for ***designing, testing and evaluating*** any supply chain, logistics and maintenance support for any DoD mission, any ad hoc mobile network, materiel (for example futuristic net-centric platforms), any large-scale complex SoS, and so on. More importantly, it fits the hybrid-model consisting of Carley's work, agent-based modeling and simulation (ABMS), and Service Oriented-Architecture (SOA)-Based Cloud Computing Model [Nyamekye June 2010], as previously noted. For example, we can use the SOA to create the packages in MMF model. In Level-2 of MMF, we can use Cloud Computing Model to design the network with infinite adaptability as part of the systems-of-systems, or the materiel, and so on [Nyamekye June 2010]. In Level-1 we can use ABMS to simulate the interactions among the various entities in combat operations, including the interactions between the warfighters and the adversaries. If the ABMS results do not achieve favorable mission outcomes, we can reevaluate the initial mission plan to determine the technical and scientific reasons for unsuccessful mission outcomes. We can then iterate through the entire planning process, similar in concept to the design-loop in Figure 3, until we achieve the desired outcomes. Please note that in Level-1 all the domains coexist. For example a task execution requires situation awareness of the enemy, which occurs in the cognitive domain. Interaction among the warfighters occurs in the social, physical and information domains. Interaction among the warfighters would require communications among the warfighters in a dynamic environment, such as in counterinsurgency operations, which implies that we should ***design, test and evaluate*** self-healing and adaptive ad hoc mobile systems to support the warfighters to achieve favorable mission outcomes.

CONCLUSIONS

The paper establishes technical and scientific architecture for testing and evaluating the Net-centric Ecosystem. Borrowing from the *Power to the Edge* concepts, the paper discusses the four domains of the Net-Centric Enterprise. The paper then emphasizes that though ***test and evaluation*** are not directly mentioned in the *Power to the Edge*, it is quite evident from Alberts al.'s work that we must address the four domains when ***designing, testing and evaluating*** each component. Using a hybrid-model of Carley's work, Axiomatic Design, MMF, agent-based modeling and simulation (ABMS), and Service Oriented-Architecture (SOA)-Based Cloud Computing Model, the paper then discusses in detail hypothetical architecture for establishing the technical and scientific basis for testing and evaluating Net-Centric Ecosystem.

Another major finding is that we can use Missions and Means Framework model for not only planning and execution of a DoD mission but also we can use it for ***designing, testing and evaluating*** the Net-Centric Ecosystem. This finding is significant because recent publication suggests that despite the significant amount of money spent by the DoD to develop a "net-centric" capability, the DoD has been unsuccessful, Figure 8.

EXPERT: AGILE CAN HELP THE DOD SAVE ITS PROJECTS

The U.S. Department of Defense has spent 10 years and more than US$100 billion to develop a "netcentric" capability—the notion of effective distributed collaborative processes around information processing, and its efforts have been largely unsuccessful. The solution—adopting more agile, collaborative processes—could apply to any large organization, said Chris Gunderson, research associate professor of information science at the Naval Postgraduate School.

The DoD has very little to show for its efforts due to an over-reliance on waterfall methodology, as well as a bureaucratic firewall between government and industry experts, said Gunderson. "Waterfall is appropriate for building nuclear missiles, but it can't be used to build everything. With those parallel problems, it's too ponderous a process to succeed," he said.

"The only success cases for distributed processing ride on top of the Web," he said, adding that eBay, FedEx and Google are successful examples.

The military has been discovering what processes work in the world of the Internet (collaborative, business processes, and open source), why they work, when they work, and how they scale, Gunderson said. But a "clumsy government acquisition process" gets in the way when it tries to co-opt those processes.

When the DoD attempted to transform itself into a network-centric enterprise, "two worlds were colliding," he explained. "It is delivering information processing capability like people built battleships in the old days."

Concepts such as open module design, spiral development and other commercial best practices don't scale inside the "metaphorical firewall" of the DoD system, Gunderson explained. He said that the private sector success cases were "predicated on massive economy of scale, reuse of components, and competition in the field."

They also met the requirements of end users. Given the constraints the military operates under, "My community advocates that agile is only way to go," Gunderson said.

Chris Gunderson says that waterfall development does not work for all projects.

However, there has been some progress in creating new government systems outside the confines of the DoD's rules and regulations, Gunderson said.

The government had an "odd success" in the creation of the IRS e-file system, by introducing open-source intellectual property to the financial community and by creating a commercial ecosystem, Gunderson said. "It also mitigated the commercial risk by providing a governance and certification model—the parameters of a level playing field."

The National Weather Service is another success case. When the Weather Service began giving away the results of its weather research, it worked on commercial standards for capturing and exploiting data, he said. "There is now a robust community of value-added weather services. The [return on investment] is obvious." ▯

—David Worthington

Figure 8. Agile Can Help The DoD Save Its Project. [SD Times, Page 5, November 1, 2009: With Permission From Dr. Chris Gunderson.]

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AUTHOR BIOGRAPHY

Dr Kofi Nyamekye is the President and Chief Executive Officer of Integrated Activity-Based Simulation Research, Incorporated, formerly known as Nyamekye Research & Consulting (NRC). Through his career, he has developed the educational, research and industrial experience to design and operate any manufacturing production system. As an educator (a former college professor) and a researcher, Dr. Nyamekye has published extensive articles on the design and operation of Cellular Manufacturing Production Systems and Simulation and Modeling of the Traditional Manufacturing Processes. Dr. Nyamekye has received many awards, among them the *1994 Educator of the Year Award from the St. Louis Society of Manufacturing Engineers Chapter 17 and the 1996 Best Paper Award selected by the Engineering Division of the American Foundrymen's Society*.

Under a large research grant from the U.S. Department of Energy, he pioneered a computer simulation model for the mold failure of the permanent mold casting process. The model will play an essential part as a federate in a distributed enterprise simulation model for automobile manufacturing supply chain federations.

Dr. Nyamekye is a member of the National Institute of Standards and Technology (NIST) International Consortium of Research Scientists called the IMS MISSION. The goal of the MISSION is to integrate and utilize new, knowledge-aware, technologies of distributed persistent data management, as well as conventional methods and tools in various enterprise domains, to meet the needs of globally distributed modeling and simulation. Under a grant from NIST, Dr. Nyamekye has established the methodology for designing Activity-Based Simulation (ABS) System as a federate in the NIST distributed enterprise simulation model for the NIST IMS MISSION. The NIST federation uses the High Level Architecture Run-Time Infrastructure (HLA RTI) architecture. The ABS uses the entity relationship (E-R) modeling technique for designing an Activity-Based Costing model with input data from the simulation federates for supply chain optimization.

Recent emphasis on Activity-Based Methodology by MITRE and Lockheed-Martin, for Service-based simulation of NCW and emphasis on Activity-Based Simulation by the Navy Modeling and Simulation Office [NMSO, http://nmso.navy.mil/glossary.cfm], have made Activity-Based Simulation the essential concept for dynamic simulation and optimization of Service-Oriented Architecture (SOA). Dr. Nyamekye has extensive prior experience as a senior research scientist in modeling and simulation of *complex adaptive distributed enterprise systems* for Boeing's Army Future Combat Systems. Dr. Nyamekye has previously published with other investigators the concepts for designing information system architecture for the wired battlefield. He has also recently established the scientific base for designing re-configurable C4ISR SOS [***Nyamekye June 2007***, http://www.dodccrp.org/events/12th_ICCRTS/CD/iccrts_main.html, ***C2 Technologies & Systems, #220***].

Dr. Nyamekye is also a member of the NIST Simulation Standards Consortium, and American Society for Engineering Education (ASEE). He chaired the session for "Design and Testing Complex Systems" in the International Test and Evaluation Association (ITEA), 2009 Annual Symposium, September 28 - October 1, 2009, at Baltimore, Maryland.

Dr. Nyamekye holds a PhD in Industrial Engineering from Pennsylvania State University, an MS in Mechanical Engineering from Pennsylvania State University, and a BS in Mechanical Engineering from the University of Wisconsin. He can be reached at kofinsoyameye@earthlink.net.