A Framework for Enterprise Systems Engineering Processes

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Abstract: In this paper, we describe how traditional systems engineering processes, such as those delineated in the ANSI//EIA 632 standard, are becoming inadequate for today's complex systems, in which there is a rich set of interconnections and interrelationships between all of the systems in an enterprise. We further suggest that a new discipline (or an extension of the old discipline) is developing in response, called *Enterprise Systems Engineering* (ESE).

We next explain some salient characteristics of complex adaptive systems and motivate how these properties, such as variation, interaction, and selection can be used to shape the evolution of the enterprise. We outline five important new processes: Technology Planning, Capability-Based Engineering Analysis, Enterprise Architecture, Strategic Technical Planning, and Enterprise Analysis and Assessment that can be used to exercise a degree of control beyond that which can be afforded by traditional means.

Key words: Enterprise Systems Engineering, Evolution, Variety, Selection, Process, Enterprise Architecture, Capabilities

1. INTRODUCTION

In 1999, the Electronic Industries Alliance (EIA) published their *Processes for Engineering a System*. This has become an American National Standard (ANSI/EIA 632), and is consistent with the approach being taken by the International Standards Organization's standard ISO 15288. In addition, the Institute of Electrical and Electronics Engineers (IEEE) standard 1220 represents an application of EIA 632 to the electronics and electrical industry. The INCOSE systems engineering process, shown in Figure 1, is based on EIA 632. Thus, the world has converged on a systems engineering standard. Although widely adopted and accepted, this model may prove to be inadequate for today's enterprise environment, where no single management entity has control over the whole.

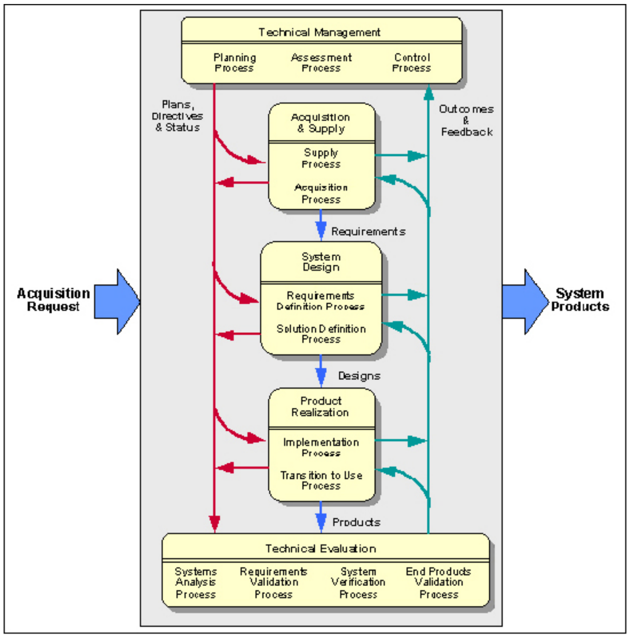

Figure 1. ANSI/EIA 632

Consider, for example, the World-Wide Web (WWW). Who is in charge of the Web? Who determines its requirements and makes its products? Who funds and schedules the rollout of its components? The WWW may be the best example of an "enterprise" as this paper envisions it. It is much more than just the satisfaction of a user requirement within budget and time constraints (and with the appropriate level of quality, dependability, etc.). The WWW is governed (mainly) by the "World-Wide Web Consortium" (W3C), which is a collection of "stakeholders" (developers, users, etc.), who have an interest in its operation and evolution who collaborate to produce the standards by which the WWW operates. Could the current INCOSE systems engineering model suffice in this environment?

The INCOSE model shows how to transform needs into a system. It includes a total of thirteen processes in four areas. For example, the System Design area defines basic tasks, such as Define the System Objectives, Requirements, Evolve Design and Operations Concepts, Select a Baseline, Verify that the Baseline Satisfies the User, and Iterate the Process through Lower Level Analysis. At The MITRE Corporation (a not-for-profit Federally-Funded Research and Development Center), we have been interested in extending systems engineering into the enterprise context (DeRosa 2005, Kuras and White 2005).

But what's missing? Even the simplest systems interoperate with and are interdependent with other systems in the broader enterprise. Their development processes follow organizational vision, goals, and governance, necessarily changing as political and financial environments change. Their requirements change as the people who operate them adapt the processes for their usage. They evolve as technology evolves and matures. Traditional Systems Engineering (TSE) does not naturally account for these complex, adaptive influences. Thus, we consider Enterprise Systems Engineering (ESE) to be an augmentation of Traditional Systems Engineering (TSE) with people, processes, and technology, subject to external ("environmental") influences.

We can represent systems engineering in the enterprise context as shown in Figure 2. The left-hand side of the drawing indicates that any system under development is embedded in a network, and the right-hand side of the drawing indicates that, in developing any system, we must consider the people, processes and technology that make up the system as well as its environmental stresses.

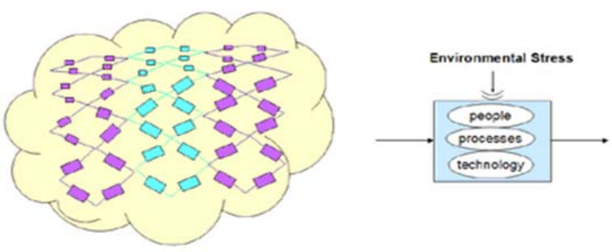

Figure 2. People, Processes, and Technology Interacting

2. ENTERPRISE SYSTEMS ENGINEERING

2-1 A New Discipline

The burgeoning discipline of *Enterprise Systems Engineering* (ESE) is consequently developing to deal with complex adaptive systems. ESE extends the TSE discipline and processes in new and different ways. Although the ESE state-of-the-art is still quite immature, the interest and potential benefit of developing such a discipline is extraordinarily high because of the pervasive nature of the internet, wireless communication, ubiquitous computing, intelligent agents, non-hierarchical control, etc.

We define an *enterprise* not as a business entity, nor a very large system, nor even as a system-of-systems, but an entity arising from taking a completely different perspective suggested by these complex behavior patterns. It is not simply a matter of scale. We consider an enterprise to be a collection of systems whose operational capabilities are inextricably intertwined with considerations of people, processes, and technology, whose boundaries are often imprecise, and which can often be characterized by a set of special, additional properties, such as emergent behavior, non-determinism, and environmental dependencies. ESE also considers the entire environment in which the system(s) must operate, including, but not limited to, the human-machine interface, the governance structure, maintenance and support, etc. The architecture of the enterprise and both its explicit requirements and implicit potential capabilities will evolve and emerge as trends in technology, scope of the enterprise, the aggregate user base, and other factors evolve over time.

Emergent behavior occurs when a collection of systems operate in an environment that enables different, often more complex, behaviors than could have been predicted by observing their individual characteristics. Thus, an enterprise’s behavior is often unpredictable and may represent a new level of the system's evolution. The challenge to the enterprise systems engineer is to exploit these new, emergent capabilities for the user community’s benefit.

The number of interactions in an enterprise increases exponentially with the number of systems, thus potentially allowing for many new and subtle capabilities and behavior patterns to emerge in non-deterministic ways. The challenge to the enterprise systems engineer is to characterize and constrain the enterprise’s complex behavior so that its evolution, while not predictable, is controllable.

The environment of the enterprise includes not only the systems of which it is composed, but the people (i.e., organizations), processes (e.g., governance and standards), and technology that surround it and profoundly effect its operation and evolution. The challenge to the enterprise systems engineer is to understand and adapt to these environmental dependencies so that the enterprise can evolve in response to changes in its environment while remaining stable and controllable.

2-2 Variation, Interaction, and Selection in Complex Adaptive Systems

If we are to treat an enterprise as a complex adaptive system, we must take into account that variation provides the “raw material.” Consider some well-known examples: VHS vs. Betamax, PC vs. Macintosh, MS Windows vs. Linux, Blu-ray vs. HD-DVD, etc. Variation brings innovative strategies into the enterprise which take the form of new technologies or new processes for doing things that serve enterprise needs. Variation increases the choices available to the enterprise, and more choices increase complexity. In most situations variation is healthy for the enterprise and can be exploited.

Interaction patterns shape the events in which members of a complex system become directly involved and provides the opportunities that lead to creation and destruction of varieties. Interaction patterns help determine what will be successful and help shape the dynamics of the interaction patterns themselves.

Finally, selection can be employed to promote healthy adaptation. This involves making decisions on which strategies should be proliferated and which eliminated.

2-3 Shaping the Enterprise through ESE processes

ESE addresses the whole of the enterprise as a complex adaptive system. Processes are the means to achieve productive ends and to shape the evolution of an enterprise. DeRosa and McCaughin (2005) described how ESE processes create a balance between the complementary enterprise behaviors of effectiveness and efficiency. They further showed that complexity is the enterprise characteristic that yields effectiveness, as order is the characteristic that yields efficiency. ESE processes shape the balance between complexity and order by influencing the amount of variation and selection introduced into the overall development process.

We should say a word about Capability Maturity Models Integration (CMMI). Traditional CMMI is directed at improving the quality of a system by improving the quality of the processes producing it. It provides a framework by which we can measure and improve efficiency and quality (measured in fewer defects.) Thus, CMMI concentrates on only one of the dimensions we engineer in complex systems—that in which selection of options produces order which, in turn, yields increased efficiency. Enterprise processes generalize the notion of CMMI to include the dimension in which a variety of strategies produces complexity which in turn yields increased effectiveness. Such a model increases order and complexity in a balanced way to produce the combination of efficiency and effectiveness that best fits the enterprise goals. A generalized CMMI model has not yet been developed for ESE.

One can view these processes as being more what a gardener does in tending a garden than what a watchmaker does in making a fine timepiece. A thoughtful gardener takes several steps: (1) takes advantage of what's available in the soil, the climate and seeds; (2) plans the crops to be harvested; (3) lays out framework for the placement and timing of crops; (4) plans the strategy for implementing the garden adapting universal tools and techniques to the local environment; and then adopts a regimen of fertilizing, watering, weeding to match the unfolding of the growth of the garden and the unfolding of the environmental conditions. The watchmaker, however, has long since defined the precise requirements, procured the totality of materials and executed assembly of a timepiece that is easily repeated. The images of the gardener and watchmaker are good metaphors for ESE and TSE.

DeRosa, Swarz, and Rebovich (2006) proposed five ESE processes designed to shape the evolution of an enterprise through a balance of actions that promote efficiency and effectiveness: Technology Planning, Capabilities-Based Engineering Analysis, Enterprise Architecture, Strategic Technical Planning, and Enterprise Assessment and Analysis, as shown in Figure 3, below. The right side of the figure represents the EIA-632 processes for engineering a system. The left-hand side represents business processes derived from Gharajedaghi and the middle section includes the five ESE processes.

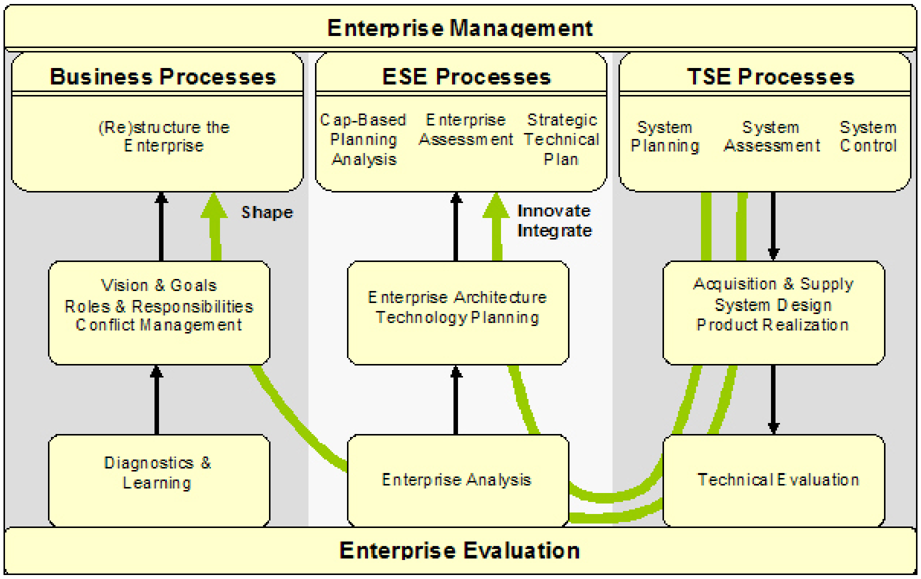

Figure 3. ESE Processes

3. IMPLEMENTING ESE

For each of the ESE processes defined, we have built a process toolkit. The philosophy employed is similar to that of our traditional CMMI processes. The toolkits guide engineers in the development of the engineering processes that support development of their system components in the context of the larger enterprise.

Each toolkit gives guidance on the use of the toolkit. It advises that if you do not have that particular process in place, you use the toolkit to define and implement it, and if you do have one in place, to tailor and monitor it. A "Process Assets" section outlines standard process elements, steps in the process, and tailoring guidelines. Then it lays out the compliance features consisting of process goals and self-assessment. It has a subsection calling for any policy that drives the process, and lastly has a place for relevant references. A "Support Assets" section of the template calls for procedures and tools and techniques. It augments that with any available training, and then gives case studies to clarify the material. A process diagram is called for to illustrate the totality of the process. All of this is available to all staff on the corporate web site.

We next present the essential elements of the toolkits for each of the five ESE processes. Each of these processes is currently being piloted in one or more programs at the Electronic Systems Center of the U.S. Air Force Material Command.

4. THE ESE PROCESSES

4-1 Technology Planning

Technology Planning develops and assesses technical opportunities in the marketplace. Development favors innovation, and assessment favors integration.

The purpose of Technology Planning process is to watch trends in both the commercial marketplace and the research community. For example, the Internet brought us the Internet Protocol (IP) as the pervasive communications protocol standard. The World Wide Web established the hypertext transfer protocol (HTTP) and ushered in the era of "pull" verses “push” of information exchange. The Extensible Markup Language (XML) became the preferred standard for data representation. The “dot-com” boom-turned-bust left us with an N-tier architecture firmly in place as the structure of choice for information systems. Watching such trends helps establish the technical strategy and implementation guidance in the Strategic Technical Plan. It defines which technologies and strategies are in the R&D phase, which are in the experimental phase, which are preferred options, and which are so pervasive as to be mandated.

The most effective technology is used in systems development and acquisition. The identification of technology that satisfies system needs and corrects shortfalls is necessary for the successful acquisition, integration and sustainment of systems. All system components must maintain a current awareness and working knowledge of applicable technology and actively plan for their incorporation into the enterprise. To accomplish this, the technology planning process will achieve three primary outcomes: (1) identification of technology needs, (2) assessment of technology maturity, applicability, and effectiveness with respect to system application, and (3) planning for technology transition to a sustainable product.

Technology Needs. The development of optimal technical solutions to solve functional objectives requires an in-depth understanding of those objectives and available or emerging technologies. To this end, it is necessary to remain current with the existence, capabilities, and status of existing and emerging technologies and to continually answer the question: “What technical characteristics or desired services must be achieved to satisfy an functional objective?”

Technology Assessments. For a technology or group of technologies to be considered an acceptable solution to a functional objective, it is necessary to assess the maturity, capability, reliability, supportability, maintainability, and interoperability of candidate technologies. The assessment should also include a comprehensive understanding of the risks and potential impact of adopting the proposed technology.

Technology Transition. Merging an accepted technology solution into the enterprise needs to be integrated with overall program planning and funding for all the programs affected. It should also be merged in a logical manner that most effectively provides delivery of services to the AF Enterprise.

4-2 Capabilities-Based Engineering

Capabilities-Based Planning (CBP) is a business process that manages the evolution of the enterprise as an interrelated set of capabilities, rather than a set of systems or programs. Capabilities-Based Engineering (CBE) is the disciplined engineering process (technical framework) for purposeful evolution of the enterprise. CBP and CBE take a holistic view of the enterprise and define capabilities in terms of the big picture. In doing so, they define issues from an enterprise perspective, rather than from a Program perspective. They set goals that the programs use to produce variety, i.e., competing strategies to accomplish those goals. CBE is the first step in what Ackoff and Gharajedaghi call idealized design. It operationalizes the most exciting vision of the future. We describe three key process modules.

Purposeful Formulation Process Module. This module establishes the framework for analysis and synthesis of the enterprise as a purposeful systems (see Ackoff & Emery 1972). It has several key steps:

- <u>Assess Stakeholder Interests</u>. Knowing the range of stakeholder interests is the first step. This makes apparent to stakeholders any conflicting demands and involves them in a participative process to dissolve conflicts.
- <u>Specify Outcomes Spaces</u>. This step defines in simple but broad terms desired enterprise outcome spaces, that is, the operational goals, contexts, and conditions which solutions address. It stimulates variety in the solution set.
- <u>Frame Capability Portfolios</u>. Capability portfolios gather together all the structural elements that must cooperate over time to provide the desired operational outcomes in capability areas.

Exploratory Analysis Process Module. This module assesses the technical feasibility and operational viability of various courses of action. It includes several key steps:

- <u>Assess Performance and Cost</u>. The performance and cost of portfolio options is assessed over the broad range of formulated contexts and conditions. Critical capability drivers, capability gaps, and possible areas of significant improvement are identified in terms of the ability of concepts and systems to achieve the desired outcomes.
- <u>Determine Need for More Variety</u>. By assessing the risks and opportunities from the foregoing capability analyses (e.g., mission shortcomings, excessive costs, or hypothesized opportunities for significant performance improvements), decide whether additional solutions are needed. A decision to explore alternative solution concepts may proceed in parallel with continued portfolio planning. This leads to a time-dependent CBP process linked to a portfolio evolution strategy.
- <u>Explore Additional Concepts</u>. This activity represents a comprehensive effort to identify possible changes in the enterprise architecture or implementing technologies that will generate additional concepts. The focus on capabilities, verses existing solutions, should facilitate thinking about new ways and means to accomplish a mission, and thus, potentially foster new transformational capabilities.

Evolutionary Planning Process Module. The previous two options determined where we wanted to go and what courses of action we might take to get there. This module forms the basis for selection of the winning options.

- <u>Examine Evolution Strategies</u>. Examine and integrate alternative evolution strategies. Construct time-phased cost and performance profiles for different evolution paths. Such strategies must typically integrate (or at least de-conflict) component program planning, budgeting, and decision-making.
- <u>Assess Enterprise Impacts</u>. Asses plans for their impacts (technical, capability, and resource) on other capability portfolios and the broader enterprise. Evolutionary planning activities are conducted at various compositional levels (e.g. program, portfolio, and enterprise), typically distributed among various organizations. Different stakeholders may manage programs that contribute to a particular capability, and a program may well support multiple capabilities. Such complicated interrelations present challenges for

evolutionary planning, and as in all CBP modules, establishing partnering relationships across the enterprise is critical.

- Select Concepts. Select capability solution alternatives, constrained by fiscal realities, acceptable degrees of risk and potential opportunities. Provide information and supporting analyses that will most influence selection decisions. Balance the adequacy of covering the decision trade space with the need to not delay decisions.
- Develop Portfolio Roadmap. A capability portfolio roadmap documents the analysis, planning, and decisions for the future of a capability area. A roadmap is used as a fundamental capability planning and management tool to enable the development of materiel solutions which meet the user's needs. A roadmap provides an integrated, time-phased, and fiscally-informed plan that assists in conducting capability assessments, guiding systems development, and defining investment strategies. A roadmap is also used as a basis for aligning resources and as an input to strategic guidance documents, program development, and program reviews.

4-3 Enterprise Architecture

Enterprise Architecture represents the vision, strategy, and implementation at the enterprise scale. It promotes self-synchronization for both developers and managers.

The vision is represented by the Enterprise Architecture. In essence Enterprise Architecture is the highest level of guidance or framework. It describes the components in an enterprise, their roles and their relationships. It can be further described as a strategic information asset base, which defines the business mission, the information necessary to perform the mission, the technologies necessary to perform the mission, and the transitional processes for implementing new technologies in response to the changing mission needs. Enterprise Architecture includes a baseline architecture, target architecture, and transition plan." It represents a framework for an integrated strategic view of the enterprise across the various dimensions of the value chain.

There is general recognition that Enterprise Architecting (EA) within Enterprise Systems Engineering (ESE) will differ somehow from "traditional" EA activities. The differences relate initially to recognition that an enterprise's interests are more diverse than the interests found historically at the systems engineering level and across the system-of-systems engineering area. Additionally, the skills, tools, techniques, and practices supporting this different kind of "next generation" EA are still maturing and not fully deployable for uniform and universal use.

The international community has already come to similar conclusions in its report from the International Federation for Information Processing (IFIP) Technical Committee C5/Working Group 5.12 (TC5/WG5.12) regarding enterprise integration efforts. This working group drew the following conclusions about the state of the practice regarding enterprise engineering:

- Large, complex problems need an interdisciplinary approach to integrate expertise, processes, and infrastructure and are not easily amenable to decomposition
- While models (and related architectures) can make knowledge more explicit, historically, they have focused more on production aspects of the enterprise, rather than on other aspects of interest to the enterprise, such as:
    - Uncertainties, unknowns, and unknowables
    - Social and cultural collaborative dynamics (including trust)
    - Investment and capital
- Integration at the level of models is a foundation requirement to architecturally relating different domains, enterprise views, and generic types
- Models must be dynamic and continuously changing to reflect responses to changing conditions and objectives

We adopted the approach that the EA process should be oriented to the capture of enterprise knowledge important to the enterprise, including aspects discussed above, and that this knowledge should be made readily available to the entire enterprise community at large (not just the architects). This "next-generation" EA process within the ESE discipline recognizes some differences in emphasis in certain EA areas from our "traditional" EA activities in several important ways.

We should restrict the scope of the EA by excluding irrelevant external architectures but extend the scope to include elements that document and relate to the enterprise's goals and strategies and its ability to adapt to them.
Deliver a federated architecture that allows the enterprise to continuously fulfill its (potentially changing) goals while responding rapidly and efficiently to external and internal needs for change.

4-4 Strategic Technical Planning

As forward-looking organizations plan their enterprise architecture and initiatives, they quickly come to the realization that the technology challenges they face are actually the easy part. Far more challenging are the organizational and management issues they must overcome to successfully meet the collected goals. An important part of controlling the evolution of the enterprise is to develop and make all components of the enterprise adhere to a single technical broad and overreaching technical strategic, which we call the Strategic Technical Plan (STP).

Gharajedaghi has argued that socio-cultural systems are bonded together through an agreement based on a common perception. The STP represents a shared technical image for the enterprise. Moreover, to promote social learning of the enterprise as a whole, the shared image must be simple and comprehensible.

STP Creation. The creation of the STP starts with <u>baselining</u> the enterprise. Although the CBE Process may have created a grand vision of what the enterprise wants to become, the evolutionary process constrains us to always start with the whole of what we have. Next comes <u>modifying</u> that baseline to take incremental steps toward that grand vision, subject only to the constraints that desired changes must be both technically feasible and operationally viable to promote the evolutionary process. Lastly comes <u>simplifying</u> the combination of the baseline, the grand vision and the incremental steps. This simplification is a critical step that differentiates Strategic Technical Planning from traditional system planning, where detailed functional specifications are often defined. Here the objective is not hierarchical control of the design, but rather a shared image of the enterprise. The created STP must be simple, understandable, widely-believed and accepted. For a modern information system, an N-tier architecture using the Internet Protocol (IP) in its network layer and a Service-oriented architecture in its application layer is one such example of tenets found in an STP.

STP Implementation. Simplification brings understandability and wide acceptance. It gets everyone in the enterprise moving in the same general direction. More detailed implementation guidance is generated as an adjunct to the STP Sometimes it is mandated and sometimes it comes from a community standards process.

- <u>Level I Guidance</u> presents standards that are so pervasive as to be key enablers of enterprise capabilities. IP is such a standard. Whether by market forces or policy, these standards are implementation mandates.
- <u>Level II Guidance</u> deals with a small number of standards that are each pervasive enough to produce efficiencies and economies of scale, but as a group are competitive enough to stimulate innovation. They represent the reality that an enterprise will always be heterogeneous. Implementation guidance must discuss the strategy for dealing with that reality. For example, many enterprises must currently deal with both .NET and Java frameworks within the information environment.
- <u>Level III Guidance</u> deals with the way in which experimental technologies may be introduced into the enterprise. The methods may include an artificial (simulation) environment, a live experimental environment, or even an operational setting in which the new technology is on-line without being in-line. Level III Guidance lays out the rules to safeguard the integrity of the enterprise.

An STP applies to all of the systems that are encompassed by the enterprise. It should be based on achieving key enterprise objectives, such as interoperability. These objectives are generally derived from capabilities derived through the Capability-Based Engineering process. It describes a common technical vision to synchronize each program's technical strategies to achieve the enterprise's objectives.

The technical strategy sets the context for planning and implementation. It is of necessity simplified, because simple strategies can be widely understood, and being understood is a precursor to being accepted. The STP embodies the Enterprise Architecture, the desired evolutionary capabilities, and the vision, goals and policies of the leadership.

4-5 Enterprise Analysis and Assessment

Enterprise Analysis and Assessment (EA&A) helps shape the environment and select options by measuring progress towards realizing the vision

EA&A is a key part of the learning and control dimension of the enterprise. It is the primary means by which the technical dimensions of the enterprise are coupled into the business decisions. It determines the enterprise-scale measures and the means by they are made. Thus, it helps identify whether the strategy and implementation are working as intended. Further, it analyzes any discrepancies between what is observed and what is expected to diagnose problems, identify risks and opportunities, and prescribe action. EA&A provides the potential for identifying break points where capabilities are either significantly enhanced or totally disabled. Thus it serves as an early warning system, an opportunity identifier, and a progress marker, and it informs business decisions at the enterprise level.

EA&A is not the ability to analyze the complete inner workings of an entire enterprise at once. It is defined in terms of an ability to characterize the behavior of entities or capabilities that are immersed within an enterprise. EA&A relates strongly to enterprise opportunity and risk assessment, emphasizing

- A robust "What If?" approach versus the traditional, highly scenario-dependent attempts at a more "predictive" approach
- Leveraging modeling and simulation (M&S) capabilities
- The ability to analyze and assess potential outcomes in a robust manner within enterprise architecture constructs to permit an understanding of fundamental behaviors

EA&A is not the ability to analyze the complete inner workings of an entire C2 enterprise at once, but it is the ability to characterize the behavior of entities or capabilities that are immersed within an enterprise.

The fundamental parts of the process are to:

- Assess an enterprise component’s status and/or value as a provider in a service-oriented architecture (SOA)
- Plan and organize for EA&A activities to reduce risk and increase opportunities
- Reach out to other stakeholder organizations for collaboration
- Modify your work program to address emerging needs as identified by the EA&A program

5. SUMMARY

An enterprise arises from taking a completely different perspective on systems, system-of-systems, and family-of systems, characterized by rich interconnectivity and complex behavior patterns. Its operational capabilities are inextricably intertwined with considerations of people, processes, and technology, whose boundaries are often imprecise and which are strongly influence by their environment. The architecture of the enterprise, with both its explicit requirements and implicit potential capabilities, will evolve and emerge as trends in technology, scope of the enterprise, the aggregate user base, and other factors evolve over time.

We have described a top-level framework for performing systems engineering in such an enterprise environment, which describes an extension of traditional systems engineering models and processes to enterprise systems engineering.

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