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A Performance-Based System Maturity Assessment Framework

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Abstract

The lack of system-level maturity has led to the development of many processes and methods for documenting, assessing, and resolving maturity and readiness. Yet, as the literature shows, there is no single integrated methodology to assess system maturity and performance throughout the lifecycle of a system, from concept development, through design, and ultimately to the operational deployment of the system. There is a need to develop a framework whereby emerging technologies and their capabilities may be evaluated up-front with an assessment conducted in terms of both technology maturity and effectiveness. The challenge is to understand the dependence or sensitivity of the technology of interest in terms of its impact on the overall system technology readiness and performance over time. The paper will lay out the specific requirements for such a framework. A system maturity metric is defined "an objective indicator or measure which facilitates system maturity level improvement". This definition will be critical in assessing measures as system maturity metrics since a critical question which is implied by this definition is "does the evaluation of the metric (and both current and projected technology maturity and associated performance) aid in improving the system maturity?" A useful set of metrics and supporting methodology must not only be used to assess the current state of the system but also provide a path to improvement. System performance measures will be introduced to provide a performance foundation for the overall framework. A key system performance measure will include projected system performance or effectiveness based on component performance capabilities. A logical assignment of relevant metrics by program phase will be made based on specific criteria. A "flowchart" type model (or logic "tree") using various readiness/ maturity models and metrics to map from system development state to desired measures maturity level will be described.
System Maturity; Performance Assessment, Technology Readiness

1. Introduction

Systems Engineering (SE) represents a variety of processes and models which are applied to various types of systems development, integration, and sustainment efforts. The application of any one of these is a result of multiple factors including, but not limited to; the industry, the domain, the organization, and the personal and professional experiences of those executing the processes. The theoretical foundations of SE provide a basis for these processes, which are then tailored to their own environment.

With such diverse SE process execution, managing the system maturity becomes a great challenge. It is therefore incomplete to postulate that a single, homogeneous method for system maturity assessment is achievable. The research to date [1] [2] [3] [4] has focused on the defense- and space-oriented domains, and has proven effective in those domains. To expand beyond this point, any attempt to manage system maturity must be based on heterogeneous mixtures of current assessment methodologies linked via a set of logical connections. An IF-THEN conditional structure which tailors the system maturity assessment to the relevant environment, using a mathematical foundation for comparison and improvement of the system maturity is required. This 'Framework'

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would require goals for determining the 'success factors' in system maturity improvement. In a traditional system development paradigm this could be tied to functional requirement fulfillment, but as is often the case, functional requirements are not enough, especially when system integration and/or sustainment are considered [5] [3]. Since the validation of functional requirements is a direct output of the SE process [6] [7] [8], and a major factor in current system maturity methods, this work will examine the problem of system maturity via performance-based factors. Specifically, how can a framework be constructed which provides the logical assessments for handling diverse systems while assessing system maturity as a function of performance-based factors?

To clarify the use of some terms in the work, the following definitions for framework, readiness and maturity are offered. Zachman [9] defines a framework as a logical structure intended to provide a comprehensive representation of a whole as separated into subparts that are mutually exclusive, unambiguous, taken together include all possibilities, and which are independent of the tools and methods used. Tetley and John [10] have addressed the importance of the terms readiness and maturity within systems engineering. They claim that System Maturity is a stateful metric which can be categorized as the being one of three states: System is Immature (SI), System Maturity in Progress, and System Maturity has been Achieved (SMA). These states exist within the process of system development, and can be associated with verification of the system. Readiness, they contend, is a Boolean value (ie. The system is either ready or not). Finally, they contend that a level above simple Readiness exists 'Capability Readiness', or the validation that the system meets the capability requirements.

1.1. Problem Definition

Given the trends in the development of defense systems, tending toward firmer up-front requirements and more cost-effective solutions [11], the Department of Defense has sought to place greater emphasis on affordability and agility [12] [13] earlier in the development of systems. Thus, given these competing forces, there is a need for a systematic understanding and assessment of the performance and readiness of emerging technologies into complex systems as they develop and evolve over time through the procurement and acquisition process. There is a particular challenge as complex systems are impacted by the development of constituent technologies at various points in the development cycle. The challenge is to understand the dependence or sensitivity of the technology of interest in terms of its impact on the overall system technology readiness, cost, and performance over time. Such a framework may be of benefit in the commercial sector as well. There is a commensurate need for a model in support of the aforementioned framework for assessing front-end technology maturity, cost, and system performance that may predict the impact of that technology on system effectiveness and overall cost as the system matures.

1.1 Background – Current Environment and Assessment Frameworks

A number of frameworks and methodologies have been proposed to address the transition of emerging technologies into complex systems. Such methods become increasingly important in the current cost-constrained environment. Sauser et al [14] apply systems maturity and development tools to technology maturity and associated cost. Koen et al [15] offer a concept development model for assessing innovation early in product development. Verma et al [16] [17] address the importance of front-end requirements to system concept design. Bodner et al [18] introduce the concept of process concurrency of complex acquisition processes and immature technologies. Valerdi and Kohl [19] propose a method for assessing technology risk through the introduction of a technology risk driver. Dar et al [20] from the Aerospace Corporation and Jet Propulsion Laboratory (JPL) conducted a comprehensive survey of risk management practices and compiled lessons learned. Technology readiness assessment approaches have been defined and applied in the literature to track the maturity and evolution of technology over time [14] [20] [21] [22] [23] [24] [25] [26] [27]. Approaches and readiness metrics [21] [22] [23] [24] [26] for technology development and readiness assessment have been developed and applied in specific instances. In addition, system of systems (SoS) have been examined to address the coordination of requirements. However, there is not a distinct link to the performance of the system; even though the technology and, in some instances, the associated cost to achieve that technology, have been assessed. DeLaurentis has applied the SoS DoD technical management and SE processes and has developed a conceptual model [28] which depicts the processes in a hierarchical fashion and represents the flow of control between the processes throughout the acquisition life-cycle. Other models [26] [29] [30] have been developed to characterize capability decisions. Again, the proposed models do not depict the performance associated with the system being developed or procured.

Mavris et al have introduced a framework called Virtual Stochastic Life-Cycle Design (VSLCD) [31] in which the lifecycle of a system is represented through optimization models and through which uncertainty may be addressed and mitigated. In other work during that time, Kirby and Mavris suggest the use of the Technology Identification, Evaluation, and Selection (TIES) method [32] for evaluating and prioritizing technologies. An Action Control Theory framework is posited by Worm [33] for characterizing complex missions. Elements of this methodology may be applied to the assessment of constitu-ent complex system technologies. Heslop et al propose the Cloverleaf Model [34], in which they evaluate technology strengths, market attractiveness, commercialization, and management support. Ramirez-Marquez and Sauser postulate an optimization model [35] for system readiness. Although these sources seek to quantitatively assess the maturity of the system or complex system of interest, there is no methodology for associating this technology maturity with the performance of the system or constituent systems.

A dynamic form of Quality Function Deployment is introduced by Ender et al [36] to identify subsystem functions associated with critical technology elements (CTEs). A critical technology element is software or hardware that is necessary for the successful development or integration of the new system [7].

The impact of varying constituent systems and sub-system technologies on technology maturity assessment of Systems of Systems is affirmed in references [37] [38] [39] [40]. Effective ways to accomplish complex system or SoS evolution given the varying development cycles of the constituent systems and technology sets are also evaluated. An extension of this methodology to characterize the performance of these functions is needed.

Ramirez-Marquez et al and others [35] [37] [41] support evaluation of strategies for effective integration of constituent systems into systems of systems [35] [41] [42]. A number of sources [43] [44] [42] assert the importance of growth of the constituent systems or subsystems within a complex system when adapting to multiple SoSs or complex sys-tems. Potential follow-up work could represent the effects of this adaptation on the performance of such systems or constituent systems. There is a need for a framework [45] to define the front-end concept and cost effectiveness upon which technology maturity may be assessed and tracked as the system and/or constituent systems mature. Sauser et al [46] investigate the impact of cost and earned value in assessing technology maturity. Mandelbaum [4] makes the case for the selection of critical technology elements based on systems supportability cost and time.

Azizian et al. [21] presents a review of maturity assessment approaches which analyzes and decomposes these assessments into three groups qualitative, quantitative, and automated. The qualitative group consists of Manufacturing Readiness Levels (MRLs), Integration Readiness Levels (IRL), TRL for non-system technologies, TRL for Software, Technology Readiness Transfer Level, Missile Defense Agency Hardware TRL, Moorhouses Risk versus TRL Metric, Advanced Degree of Diffuculity (AD2), and Research and Development Degree of Difficulty (RD3). These metrics are then assessed utilizing the SWOT (Strength Weakness Opportunity Threat) model which reveals that while each is able to excel at individual assessments, none provide a complete picture of complex system maturity. Next, the quantitative group consists of SRL, SRLmax, Technology Readiness and Risk Assessment (TRRA), Integrated Technology Analysis Methodology (ITAM), TRL for Non-Developmental Item Software, Technology Insertion (TI) Metric, and TRL Schedule Risk Curve. The SWOT analysis points to the fact that while the metrics are inclusive and robust, their complex mathematical calculation are not ideal for rapid, iterative analyses and can be prone to simple mathematical errors during calculation. However, it is noted that the fact that these metrics provide tangible data for decision making outweighs these shortcomings. Finally, the automated methods of TRL calculator, MRL calculator, Technology Program Management Model (TPMM), and UK MoD SRL are assessed. It is found during the SWOT analyses that the automated methods combine some of the best qualities of both the qualitative and quantitative, but also some of their issues, namely the fact that most of the methods involve the answering of questions, which can be misinterpreted or just simply incorrectly answered. These metrics represent the current state of system maturity and readiness assessment, and must be explored to determine what significance each adds and how they interrelate.

1.2 Defining a Metric

In order to begin to assess, categorize, and integrate metrics it is necessary to start with a clear definition of what a metric is, and more importantly why they are useful in the context of system maturity, as it has been established that at the lowest level it is maturity which is to be measured [25]. Kiemele et al. [47] define a metric as: "an objective indicator or measure which facilitates process improvement". The definition is taken from a book on statistics as applied to quality control processes; yet if the "process" portion of the definition is replaced with "system maturity level", a reasonable definition for the context of the research is achieved. Thus, for this work a system maturity metric will be defined as: "An objective indicator or measure which facilitates system maturity level improvement."

2. Towards a System-Maturity Assessment Framework

The framework for approaching the problem of inter-disciplinary technology management must be one which addresses the issue from multiple directions, and focuses the best practices of the various domains to provide value to the system in the form of a focused and accurate system maturity plan. This plan is one of the outputs of the framework and is derived from the answers to a set of the most basic systems analysis questions, or elements of the analysis. Sauser and Boardman [48] address these in the form of "what, why, how, where, and when, and this work will adapt that format in formulating the specific questions and seeking answers. These questions are provided as a starting point and may be adapted and/or extended based on the scope and circumstances of the system under development. The technology, integration, and system maturity metrics described previously will form the base from which the answers to these basic queries will be used to filter the metrics and provide a logical assessment from which a plan can be formulated.

2.1 Where

First we must identify where we are in the system lifecycle as the system should be handled differently based on what lifecycle phase we are currently in. If we are early in concept development, or requirements derivation, etc we should handle the TRL and IRL evaluations and risks differently than if we are in the I&T, initial operations, or sustainment phases. Buede [49], ISO 15288 [8] along with others [7] [3] [50], provides the lifecycle phases which can be selected as an enumerated set: development, manufacturing, deployment, training, operations and maintenance, refinement, and retirement.

2.2 What

The system architecture is a major focal point for how the system is integrated and can drive how the integration and system maturity is evaluated, some basic architecture are client-server (hierarchical) or distributed (directed graph). Yet in modern systems theory one must also account for service-orientated, virtual, and cluster architectures which further complicate the evaluation. The system architecture should be documented as a graph of some form which can be abstracted to a level where graph theory can be applied to the assessment. At this point, the preceding logic must begin to be applied, if we are in early system development, the architecture as a whole may need to be evaluated from a reliability, sustainability, and maintainability perspective, yet, if we are in refinement, then we may consider the integration of a new component or critical technology element (CTE) and its interaction with the architecture.

2.3 How

This question could also be ‘how hard is it to mature the system?’ or ‘how do I maintain maturity in a technology insertion?’ To provide this sort of data requires an in-depth technical understanding of individual CTEs and their projected paths to maturity within the system. The organizations/teams/leads responsible for the various CTEs need to provide transparent data on CTE progression and maturity. Metrics such as TRL, IRL, R&D3, delta-TRL, etc should be assessed regularly [51] [52]. Logic applied based on the lifecycle and architecture can be used to weigh and apply these metrics.

2.4 When

Simply put, this question is ‘what is my schedule’; again this portion is greatly dependent upon the lifecycle phase and when the transition to the next phase needs to occur. The idea here would be to analyze the current traditional metrics of Earned Value against the ‘systems maturity metrics’ already obtained for each CTE, as it related to the system architecture. For example, if we are about to transition to integration and test, under a client-server architecture and one client-CTE has a low IRL(s), high-delta TRL, but low R&D3 then there may be less risk than a server-CTE with high IRL(s), low-delta TRL, but high R&D3 relating some specific function(s). The evaluation of whether to continue, or start moving more resources towards either element, must be underscored with a reason, which brings us to the final question.

2.5 Why

This question could be reframed as ‘Why are we integrating these components?’, or ‘Why do we need this?’ We contest there are two, very different, but equally important answers to this question which get to the core of the Systems Engineering Process: Functional vs Performance requirements. Essentially, functional requirements demand that two or more CTEs be integrated into a system which meets the requirements that neither of the individual CTEs could meet independently, a basic example of ‘the whole is greater than a sum of the parts.’ Performance requirements can be more trivial, yet equally as important. It is through this lens that we will show the final level of system maturity analysis. The performance-based analysis is not meant to replace a requirements-based one, but to complement it, since SRL, TRL, and IRL consider requirement-fulfillment, or lack there-of, inherently [51] [1] [35]. The performance-based view provides a system assessment from a non-functional standpoint while also allowing for cross-comparing of elements. The potential areas that can be addressed by this include COTS selection, CTE development direction, and technology insertion.

3. Initial Framework Structure

The Framework as described consists of a logical set of connections between the various metrics, which provides a method for evaluating and improving the system maturity. When a system is developed or upgraded the process is executed, starting with the answering of the question of “Why?” (1.0 in Figure 1) which is quantified via a performance-based assessment . The answers to the questions of “Where?” (2.0) and “When?” (5.0) are generally straight-forward and typically determined by contractual constraints. The questions of “How?” (3.0) and “What?” (4.0) are evaluated by the metrics mentioned in the background section, based on their applicability to the system lifecycle phase. In response to 1.0, a performance-based assessment is conducted. This assessment entails modeling the impact of the new technology or technologies on the performance of the system. The performance-based assessment is then compared to the output of the other processes (1.2), e.g., readiness levels (TRLs and SRL) and a final system maturity assessment (1.3) prioritizing these metrics, is conducted. The technology-performance trade space for a specific technology of interest within a complex system may be characterized by both technology metrics (e.g., TRLs/SRL) and technical performance metrics (TPMs). The final step of the Framework is to quantitatively determine if the performance gain is worth the risk, and if it is, to provide a system maturity improvement plan. The complete process is documented by Figure 1.

4. Application of Framework

We use the automobile as a sample complex system consisting of a number of systems (and associated critical technology elements) including the engine, transmission system, cooling system, braking system, and steering system. We now show how we might systematically evaluate responses to questions posed in the framework.

4.1 Why are we doing this?

To assess the reason for conducting this potential technology transition; e.g., upgrading the fuel efficiency of an automobile, we conduct a series of performance-based and technology maturity evaluations.

4.1.1 *Performance-Based Assessment*

To answer this question, we first conduct a performance-based assessment (1.1). Performance of the critical technology elements within these systems is a measurable and testable value(s) of a system-level goal to increase vehicle fuel-efficiency. Typical Technical Performance Measures (TPMs) include those factors which drive the overall goal of the system and are a function of a number of performance parameters associated with the constituent systems and associated critical technology elements. We may use models and test data to conduct this assessment.

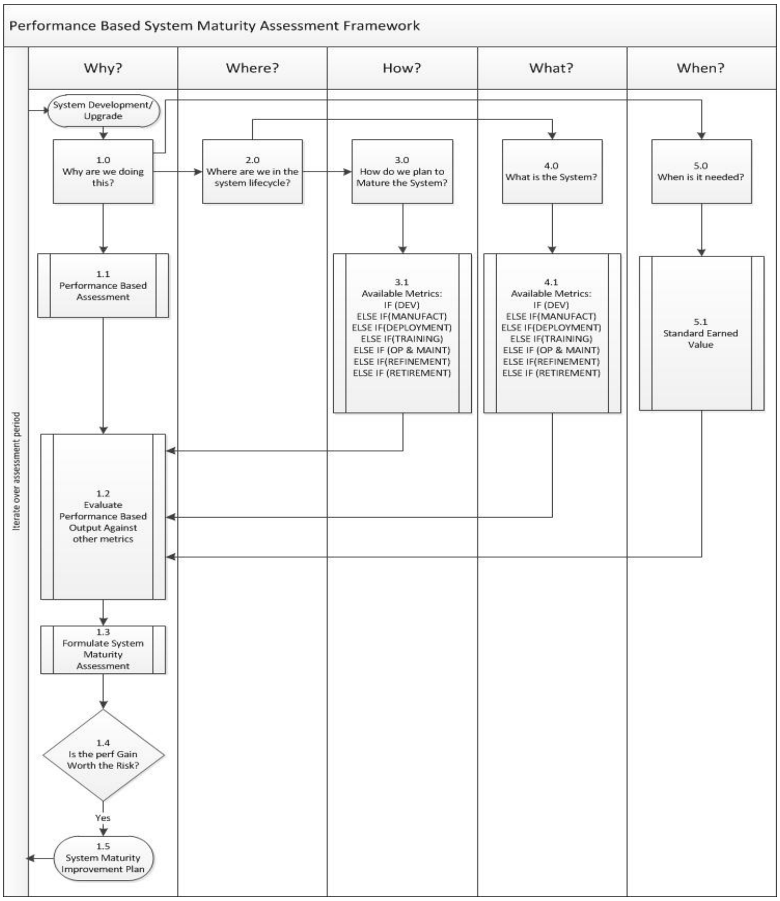

Figure 1: Performance-Based System Maturity Assessment Process

4.1.2 *Evaluate Performance-Based Outputs against other Metrics*

We then evaluate the performance-based output against other metrics (e.g., technology readiness levels) as in (1.2) in Figure 1. Table 1 demonstrates the technology-performance trade space for the automobile. The sensitivity, or impact, of key performance parameters, p_i, on overall performance, is represented by $\delta TPM/\delta p_i$. Note that a typical TPM, automobile Miles per Gallon, is a function of a number of system performance parameters (p_i) including engine fuel consumption per kilowatt of power produced, torque transmittal efficiency and parasitic losses in the transmission, fuel consumption delta produced by passenger comfort systems, and coefficient of friction as a result of the aerodynamics of the body along with the differentials. The impact of these performance drivers on the overall vehicle performance is represented by the $\delta TPM/\delta p_i$ and can assist in understanding and prioritizing critical specific performance drivers. In order to provide a quantitative example we have created some sample data; it should be noted that this data is only for theoretical purposes. This first step in the process is to answer the questions posed, and apply the framework logic. Again, for purposes of practicality, there is no scientific basis to the logic-selections of the metrics; this is simply to validate the concept of the framework. With that in mind, Table 2 is the output of the query answering process and metric selections. Note that the metrics associated with each of the questions are indicated. For example, in terms of why we are upgrading the vehicle.

Table 1: Technology-Performance Trade Space for an Automobile

Elements of Automobile	Component TRLs (TRL_i)	TPM (p_1, p_2, p_3, p_4, p_5) = automobile MPG	$\delta TPM/\delta pi$

Engine	TRL_1	p_1 = Fuel Consumption per kilowatt	$\delta TPM/\delta p_1$
Transmission	TRL_2	p_2 = torque transmittal efficiency p_3 = parasitic losses	$\delta TPM/ (\delta p_2\ \delta p_3)$
Passenger Comfort System(s) (cooling, heating, DC power, etc.)	TRL_3	P_4 = fuel consumption delta	$\delta TPM/\delta p_4$
Body aerodynamics / Differential drag	TRL_4	P_5 = coefficient of friction	$\delta TPM/\delta p_5$

the sensitivity of the MPG will directly impact the readiness and maturity of the overall vehicle as new technologies are introduced to meet the performance goal.

Table 2: Example Performance-Based Framework Query Output for an Automobile

Query	Description	Metric
1.0 Why?	Why are we upgrading the vehicle? TPM = increase fuel efficiency from 25 to 50 MPG	1.1 = δTPM/δpi
2.0 Where?	We are upgrading an existing model to create a new 'more efficient' model, so lifecycle phase = "Refinement"	null
3.0 How?	Since we are in the "Refinement" phase, we will select a metric which is appropriate, as an example, we will select "ITI"	3.1 = ITI [52]
4.0 What?	Since we are in the "Refinement" phase, we will select a metric which is appropriate, as an example, we will select "SRL"	4.1 = SRL
5.0 When?	Standard EV, along with overall schedule will be used	5.1 = EV

With the selections complete, we will now provide some sample data which would be part of the iterative assessment; this is presented in Table 3. The trending of this data should be evaluated at each assessment interval and compared to the initial and previous intervals; this is representative of the process which occurs in sub-processes (1.2), and (1.3), in Figure 1.

Table 3: Example Performance-Based Framework Evaluation for an Automobile

	Date / Iteration						
Query	Initial (Month-0)	M-3	M-6	M-9	M-12	M-15	M-18
Why?	TPM_c = 25 MPG TPM_t = 50 MPG	TPM_c = 25 MPG	TPM_c = 30 MPG	TPM_c = 30 MPG	TPM_c = 37 MPG	TPM_c = 40 MPG	TPM_c = 44 MPG
Where?	"Refinement"	"Refinement"	"Refinement"	"Refinement"	"Refinement"	"Refinement"	"Refinement"
How?	ITI = 15	ITI = 13	ITI = 13	ITI = 14	ITI = 10	ITI = 8	ITI = 7
What?	SRL_c = .45 SRL_t = .85	SRL_c = .45	SRL_c = .50	SRL_c = .50	SRL_c = .63	SRL_c = .70	SRL_c = .79
When?	in 18 Months	EV=.90	EV=.75	EV=.80	EV=1.1	EV=.85	EV=.90

As a note in the table, "_c" implies "current" and "_t" implies "target". The sub process in (1.4) is a performance-based decision which weighs the risk of moving forward against the proposed gains, in the example provided at the month-15 point, the risk involved to gain 10 MPG should have been evaluated against the previous cycle's EV spent to only gain 3 MPG. In this same iteration the SRL was progressed and the ITI slightly reduced, these metrics should have been examined in detail to plan the next iteration's focus.

5. Conclusions and Future Work

This framework is still at the conceptual stage and requires advances in multiple areas. The immediate value of this framework is the realization of the system maturity as a function of a system-level performance measure, while retaining the critical assessment data provided by other system maturity metrics. Again, the scope of this work is simply to introduce the concept of a performance based system maturity framework to the community, not to define the semantics of such a framework.

The general structure of the framework as defined in this work sets the stage for the top-down development to follow for each sub-process within the framework. With this in mind, the following areas for future improvement have been identified:

- Develop and iterate the logical assessment sub-processes for metric selection (3.1) & (4.1) – Thus far, the only dependent variable identified is the system lifecycle phase, the potential for other input variables must be investigated. In addition, the logical IF-THEN structure must be defined via intense literature review of the available metrics and validated against real-world data. It may be that an 'open' process which gets tailored to the individual organization, industry, etc is used for each sub-process.
- Define the sub-process for evaluating the performance-based assessment (1.2) & (1.3) – Similar to the metric sub-processes, defining and developing the logic and quantitative assessment processes is critical to a framework which is structured in such a fashion as to remove bias and subjectivity. In addition, criteria for making the risk-based decision (1.4) must be defined from the literature using the output of the assessment.
- As defined in the literature a metric helps to not only provide a current state assessment, but also improve the system. The framework's ultimate output should be a 'System Maturity Plan' (1.5) which uses all the information available in the assessment to highlight the areas where risk exists and needs to be mitigated to gain the largest performance improvement.

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