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USING A SYSTEM MATURITY SCALE TO MONITOR AND EVALUATE THE DEVELOPMENT OF SYSTEMS

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Using a System Maturity Scale to Monitor and Evaluate the Development of Systems

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Abstract

The readiness of a system under development cannot be adequately measured by using traditional project management tools that focus predominantly on cost and schedule. An

alternative principally utilized by NASA, the DoD and the DoE to address this has been the prescriptive metric known as Technology Readiness Level (TRL). However, TRL is only meant to measure the readiness of technology elements and does not address their integration or some other challenges of systems development.

To address integration, the Systems Development & Maturity Laboratory (SD&ML) at Stevens Institute of Technology introduced another prescriptive metric called Integration Readiness Level (IRL). Combining TRL and IRL scales, SD&ML has formulated a System Readiness Level (SRL). SRL is an aggregate measure that characterizes the progress that has been accomplished by a system under development based on the observable readiness characteristics of the technology and integration elements, not the cost and schedule values.

This paper describes the application of SRL to a constrained resource optimization model to determine an optimal development plan that identifies which technologies and integration elements should be matured to which levels such that a specific level of system readiness is achieved by a certain time. This optimal plan can be used to monitor and evaluate the actual progress of the system—it can be the basis of a systems lifecycle maturity management approach called System Earned Readiness Management (SERM). A simple example is used to illustrate SERM.

1. Introduction

"How much progress have I accomplished against my original plan?" Program managers ask this is the fundamental question in order to keep track of the development of their systems. To answer this, they have relied on assessment and evaluation tools. Abba (1997) describes the evolution of these techniques from the "Spend Plan" approach to Program Evaluation and Review Technique (PERT), which was then modified by the Navy into PERT COST in an attempt to improve cost management in 1960. Combining its own experiences with those of the Navy's, the Air Force in 1963 formulated the earliest version of an Earned Value Management (EVM) approach by developing Cost/Schedule Planning and Specification (C/SPEC) to manage the Minuteman program. This initiative evolved into the 1967 Department of Defense (DoD) Instruction called Cost/Schedule Control Systems Criteria or C/SCSC (DoD, 1967). Initially developed by financial managers, C/SCSC was primarily concerned with cost and was generally ignored by project managers who were more concerned with technical and performance considerations (Abba, 1997). In 1989, the organization within the DoD tasked with C/SCSC was transferred from the Controller's office to Acquisition. By 1995, EVM was designated as the preferred tool for managing risky, cost-based contracts (Kaminski, 1995). Along with these developments, the DoD also developed the pioneering EVM software *Performance Analyzer.* The DoD encouraged the private sector to enhance and eventually replace this software with tools that are commercially available today.

EVM as a primary tool has been credited with reducing total cost overrun on the largest, most risky DoD contracts to 5.5% by 1999, (Abba 2001). Currently, however, there is growing concern that EVM, which evaluates cost and schedule performances, does not adequately report the proper maturation of complex systems under development. In particular, while EVM is quite effective in capturing and representing the accomplishment of work packages, it is unable to state whether these completions are actually leading to the maturity of the system's critical components. Thus, it is unable to estimate the maturity or readiness of the entire system at a given time during its development. This is especially true when there is a high degree of uncertainty due to the novelty and high technological content of the system. Such systems require numerous iterations before requirements and design can be frozen. Once they are, then

EVM becomes a most effective tool. However, until that point in a system's development is reached, a different kind of assessment method is needed.

This new assessment method will require the following elements: metrics that can measure maturity of technologies—their integration links and the system itself; the identification of optimal development plans (based on these metrics) that can meet the development strategy of the system; and a mechanism for reporting the periodic status of the system against the optimal development plan so variances can be measured, explained and corrective measures may be formulated.

To begin to address these elements of an alternative or modified EVM approach, we will describe the application of a system maturity metric (i.e., System Readiness Level) and its application to a constrained resource optimization model to determine an optimal development plan that identifies which technologies and integration elements should be matured to which levels, such that a specific level of readiness is achieved by a certain time. We will then use the optimal plan to demonstrate how this technology can be used to monitor and evaluate the actual progress of a system. Thus, it can become the basis of a system's lifecycle maturity management approach, which we have defined as System Earned Readiness Management (SERM). We conclude with a simple example to illustrate SERM.

2. System Readiness Metrics

In order to measure the maturity of a complex system, Sauser, Verma, Ramirez-Marquez, and Gove (2006) proposed the System Readiness Level scale or SRL. This was eventually refined into its latest form, which was presented to this Symposium last year (Sauser, Magnaye, Ramirez-Marquez & Tan, 2008b) and later published in length in the *International Journal of Defense Acquisition Management* (Sauser, Magnaye, Ramirez-Marquez & Tan, 2008a). It combines the widely accepted Technology Readiness Level (TRL) scale (Mankins, 1995; 2002; DoD, 2005), which is used to evaluate critical technology elements and an Integration Readiness Level (IRL) scale developed by Sauser et al. (2006) and refined by Gove (2007). TRL is presented in Table 1 while IRL is shown in Table 2 below.

Table 1. Technology Readiness Levels

TRL	Definition	Description (DoD, 2005)
	Actual System Proven Through Successful Mission Operations	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "bug fixing" aspects of true system development. Examples include using the system under operational mission conditions.
8	Actual System Completed and Qualified Through Test and Demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets design specifications.
7	System Prototype Demonstration in Operational Environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in an aircraft, vehicle or space. Examples include testing the prototype in a test bed aircraft
6	System/Subsystem Model or Prototype Demonstration in Relevant Environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment.
5	Component and/or Breadboard Validation in Relevant Environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include “high fidelity” laboratory integration of components.
4	Component and/or Breadboard Validation in Laboratory Environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of “ad hoc” hardware in a laboratory.
3	Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept	Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
2	Technology Concept and/or Application Formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
1	Basic Principles Observed and Reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.

Table 2. Integration Readiness Levels

(Gove, 2007)

IRL	Definition	Description
9	Integration is **Mission Proven** through successful mission operations.	IRL 9 represents the integrated technologies being used in the system environment successfully. In order for a technology to move to TRL 9 it must first be integrated into the system and then proven in the relevant environment, so attempting to move to IRL 9 also implies maturing the component technology to TRL 9.
8	Actual integration completed and **Mission Qualified** through test and demonstration, in the system environment.	IRL 8 represents not only the integration meeting requirements, but also a system-level demonstration in the relevant environment. This will reveal any unknown bugs/defects that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
7	The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable.	IRL 7 represents a significant step beyond IRL 6; the integration has to work from a technical perspective, but also from a requirements perspective. IRL 7 represents the integration meeting requirements such as performance, throughput, and reliability.
6	The integrating technologies can **Accept, Translate, and Structure Information** for its intended application.	IRL 6 is the highest technical level to be achieved, it includes the ability to not only control integration, but to specify what information to exchange, unit labels to specify what the information is, and the ability to translate from a foreign data structure to a local one.
5	There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration.	IRL 5 simply denotes the ability of one or more of the integrating technologies to control the integration itself; this includes establishing, maintaining, and terminating.
4	There is sufficient detail in the **Quality and Assurance** of the integration between technologies.	Many technology integration failures never progress past IRL 3, due to the assumption that if two technologies can exchange information successfully, then they are fully integrated. IRL 4 goes beyond simple data exchange and requires that the data sent is the data received and there exists a mechanism for checking it.
3	There is **Compatibility** (i.e., common language) between technologies to orderly and efficiently integrate and interact.	IRL 3 represents the minimum required level to provide successful integration. This means that the two technologies are able to not only influence each other, but also communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
2	There is some level of specificity to characterize the I**nteraction** (i.e., ability to influence) between technologies through their interface.	Once a medium has been defined, a “signaling” method must be selected such that two integrating technologies are able to influence each other over that medium. Since IRL 2 represents the ability of two technologies to influence each other over a given medium, this represents integration proof-of-concept.
1	An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

The SRL scale is calculated by using a normalized matrix of pair-wise comparisons of TRLs and IRLs that reflects the actual architecture of the system. Briefly stated, the IRL matrix is obtained as a symmetric square matrix (of size $n \times n$) of all possible integrations between any two technologies in the system. For technology integration to itself, perfect integration is assumed (IRL= 9) while an IRL of zero is used when there is no integration between two technologies. Likewise, the vector TRL defines the readiness level of each of the technologies in the system. In its current form, the SRL is calculated as

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \ldots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}TRL_1 + IRL_{12}TRL_2 + \ldots + IRL_{1n}TRL_n \\ IRL_{21}TRL_1 + IRL_{22}TRL_2 + \ldots + IRL_{2n}TRL_n \\ \ldots \\ IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \ldots + IRL_{nn}TRL_n \end{bmatrix} \text{ where } IRL_{ij}=IRL_{ji}$$

and

$$SRL = \frac{\left(\frac{SRL_1}{n_1} + \frac{SRL_2}{n_2} + \ldots + \frac{SRL_n}{n_n}\right)}{n}$$

where n_i is the number of integrations with technology i plus its integration to itself.

The resulting SRL metric can be used to determine the maturity of a system and its status within the developmental lifecycle. Table 3, for example, is a representation of how the SRL scale correlates to a systems engineering lifecycle. These notional values of the SRL scale shown in Table 3 are meant to be organization-generic examples of how the calculated SRL values can be set as a guide by a systems engineer or program manager. That is, in practice the systems engineer or program manager at the outset must determine what values of the SRL correlate to that point where one phase begins and where it ends for that particular system. A calibration of these relevant ranges for each phase of system development will have to be program-specific or, at best, pertinent only to a particular class of systems that share a large degree of similarity. Therefore, the SRL value of a system can only be compared to that of the same system or a very similar system.

Table 3. System Readiness Levels

SRL	Name	Definitions
0.90 to 1.00	*Operations & Support*	Execute a support program that meets materiel readiness and operational support performance requirements and sustains the system in the most cost-effective manner over its total lifecycle.
0.80 to 0.89	*Production & Deployment*	Achieve operational capability that satisfies mission needs.
0.60 to 0.79	*Engineering & Manufacturing Development*	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; minimize logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility.
0.40 to 0.59	*Technology Development*	Reduce technology risks and determine and mature appropriate set of technologies to integrate into a full system and demonstrate CTEs on prototypes.
0.10 to 0.39	*Materiel Solution Analysis*	Assess potential materiel solution options

NOTE: These ranges have been derived conceptually and are undergoing field verification and validation under Naval Postgraduate School Contract # N00244-08-0005.

While the TRL has been widely accepted by many government and industry organizations, the IRL and SRL need continued verification and validation; efforts are currently under way. Early results indicate that SRL can institute a robust and repeatable method for assessment and reporting the status of a system's development. It enables program managers to evaluate system development in real time and take corrective actions. It can also be applied as a predictive tool for technology insertion (Michaud, Forbes, Sauser & Gentile, 2008). In order to firmly establish the validity of SRL, it must be applied to a sufficient number of real complex systems under development.

Nevertheless, a rudimentary SRL calculator has been developed by the Systems Development & Maturity Laboratory (SD&ML) at Stevens Institute of Technology (see http://www.SystemReadinessLevel.com; Tools) and is undergoing refinement. In addition, the SD&ML is in ongoing partnerships to develop tools for system maturity assessment that leverage their continued research in systems maturity.

3. Formulating Optimal Development Plans

System development is pursued based on two generic strategies: minimizing costs or being the first to market/deployment (Laugen, Acur, Boer & Fick, 2005). In order to meet these strategic imperatives, the program manager must have the capability to instruct the project managers about which technologies and integration links must be matured to sufficient levels and when. Leveraging the SRL method previously described, such a development plan can be formulated by relying on constrained optimization techniques. The methodology for cost minimization has been formulated by Magnaye, Sauser, and Ramirez-Marquez (2009) while the first to market/deployment was developed by Sauser and Ramirez-Marquez (2009). These are summarized below.

3.1. Cost-driven Strategy

The cost-driven strategy is becoming more common as political pressure (in government programs) and competitive intensity (in industry) becomes more pronounced in the current and future economic environment characterized by more constrained resources and more demanding customers. In this case, the development strategy is to optimize the allocation of limited resources while attaining a certain level of system maturity or readiness within a specified time. In order to execute the development required to reach a SRL value by a certain time, it is necessary to know how to reach this level at a minimum cost. To address these concerns, Magnaye et al., (2009) proposed an optimization model whose objective is to minimize development cost (a function of TRL and IRL development) under constraints associated with the required SRL value and schedule. This model recognizes that technologies compete for resources and that the optimal allocation of the least amount of resources to reach a certain SRL value is desirable. The general mathematical form of this model called SCOD$_{min}$ follows:

$$\text{Minimize: SCOD } (\mathbf{TRL,IRL}) = \text{SCODfixed} + \text{SCODvariable } (\mathbf{TRL,IRL})$$

$$\text{Subject to: SRL}(\mathbf{TRL,IRL}) \geq \lambda$$

$$R_1\ (\mathbf{TRL,IRL}) \leq r_1$$

$$\vdots$$

$$R_h\ (\mathbf{TRL,IRL}) \leq r_h$$

In addition to the SRL and time or schedule constraints, other possible constraints could be technical performance parameters such as equivalent mass for space systems, peak load capacities for transportation and so on.

The matrices **IRL** and **TRL** in Model SCOD$_{min}$ contain the decision variables. Each variable is integer-valued and bounded by (IRL_i,9) and (TRL_i,9), respectively. That is, the TRL/IRL for the i^{th} component cannot be below its current level or above perfect technology or integration development (IRL or TRL = 9).

To completely characterize the decision variables in Model SCOD$_{min}$, it is necessary to introduce the following transformation:

$$y_i^k = \begin{cases} 1 & \text{If } TRL_i = k \\ 0 & \text{otherwise} \end{cases} \quad \text{and} \quad x_{ij}^k = \begin{cases} 1 & \text{If } IRL_{ij} = k \\ 0 & \text{otherwise} \end{cases} \quad \text{for } k=1,\ldots 9$$

Notice that based on these binary variables, each of the possible normalized TRL and IRL in the system can be obtained as $TRL_i = \frac{\sum_{k=1}^{9} k y_i^k}{9}$ and $IRL_{ij} = \frac{\sum_{k=1}^{9} k x_{ij}^k}{9}$. Based on these binary variables SRL$_i$ is transformed to:

$$SRL_i = \frac{\left(\sum_{k=1}^{9} kx_{i1}^{k}\right)\left(\sum_{k=1}^{9} ky_{1}^{k}\right)}{81} + \frac{\left(\sum_{k=1}^{9} kx_{i2}^{k}\right)\left(\sum_{k=1}^{9} ky_{2}^{k}\right)}{81} + \ldots + \frac{\left(\sum_{k=1}^{9} kx_{ij}^{k}\right)\left(\sum_{k=1}^{9} ky_{j}^{k}\right)}{81} + \ldots + \frac{\left(\sum_{k=1}^{9} kx_{in}^{k}\right)\left(\sum_{k=1}^{9} ky_{n}^{k}\right)}{81}$$

$$= \frac{\sum_{j=1}^{n}\left(\sum_{k=1}^{9} kx_{ij}^{k}\right)\left(\sum_{k=1}^{9} ky_{j}^{k}\right)}{81}$$

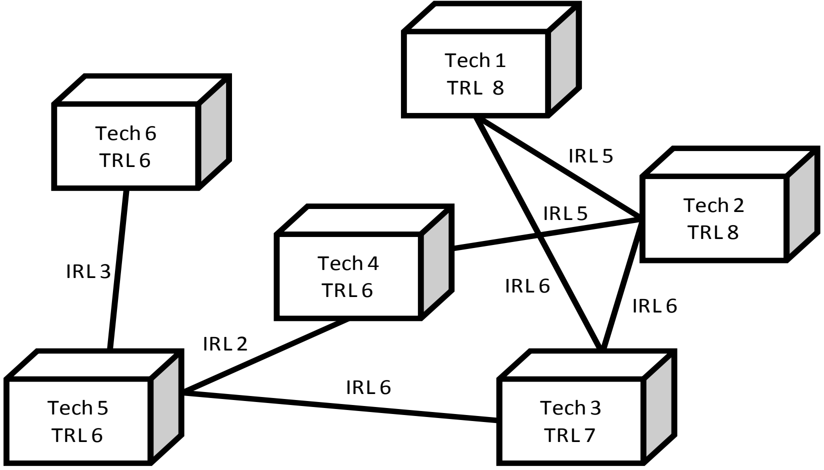
Based on the computation of the SRL with these decision variables, Model $SCOD_{min}$ belongs to the class of binary, integer-valued, non-linear problems. For a system with *n* technologies containing *m* ($m \leq (n-1)n/2$) distinct integrations, and assuming all technologies and integrations are at their lowest levels, there are 9^{n+m} potential solutions to Model $SCOD_{min}$. Evaluating each possible solution is prohibitive, so to generate a more timely optimal solution, a meta-heuristic approach developed by Ramirez-Marquez and Rocco (2008) was applied to the system under development and is described below. This approach, called Probabilistic Solution Discovery Algorithm (PSDA) has the capability of producing quasi-optimal solutions in a relatively short period of time. However, it must be mentioned that the results cannot be proven as the optimal solution because by taking a probabilistic approach, the algorithm can only select subsets of the entire feasible set from which to find a solution. Every time the algorithm is run a different subset is selected. Nevertheless, prior tests have indicated that PSDA results tend to be better than results from alternative meta-heuristic approaches (Ramirez-Marquez & Rocco, 2007).

As used in the solution of the minimization problem, the algorithm follows three inter-related steps:

- Strategy Development—a Monte Carlo simulation is used to identify the potential TRL or IRL levels the technologies and links can advance or mature;
- Analysis—each potential solution is analyzed by calculating its associated cost, schedule and SRL;
- Selection—through an evolutionary optimization technique, a new optimal set of technologies and integration links (with their corresponding TRLs and IRLs are chosen based on the cost, schedule and SRL values).

3.2. Notional Example and Results

Figure 1. System Concept Diagram



Tech 1: Remote Manipulator System (RMS); Tech 2: Special Purpose Dexterous Manipulator (SPDM); Tech 3: Electronic Control Unit (ECU); Tech 4: Autonomous Grappling (AG); Tech 5: Autonomous Proximity Operations (APO); and Tech 6: Laser Image Detection and Radar (LIDAR).

The following notional example will use a simple system of six technologies and seven integrations (see Figure 1 above) to demonstrate the steps involved in calculating the SRL value and minimizing the cost subject to constraints on system maturity and schedule. By evaluating the SRL of this system, an estimate of its actual readiness can be obtained before being deployed. In year 1 (current year), when reviewing the SRL for this system in its current state, the calculations yielded an SRL of 0.48. Referring to Table 3, this value indicates that this system should be in the Technology Development phase, with the technologies close to maturity (lowest TRL is 6) while integration elements are behind, one as low as level 2 only. For the system used in this example, Tables 4 and 5 present the *incremental* budgetary and time requirements to mature each technology and integration element from its current level to the next. For example, to mature Technology 1 from its current TRL of 8 to 9 will require another $900,000 and 349 labor-hours. In order to fully mature all the technologies and integration elements, an additional $26.574 million and 19,122 labor-hours are required.

Table 4. Estimated *Incremental* Cost (x1000) and Time for Each Technology Effort

Technology	1		2		3		4		5		6	
TRL Level	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1												
2												
3												
4												
5												
6												
7							$876	127	$467	280	$780	450
8					$689	476	$421	341	$531	236	$123	21
9	$900	349	$765	432	$734	299	$853	568	$189	48	$389	300

Table 5. Estimated *Incremental* Cost (x1000) and Time for Each Integration Effort

Integration	1,2		1,3		2,3		2,4		3,5		4,5		5,6	
IRL Level	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time	Cost	Time
1														
2														
3											$453	200	$123	80
4											$581	400	$219	380
5											$721	658	$595	532
6	$100	140					$275	164			$900	700	$700	621
7	$175	180	$200	93	$50	25	$540	320	$345	324	$1,200	954	$808	862
8	$400	300	$400	165	$450	320	$632	432	$457	400	$1,432	1021	$1,003	997
9	$600	500	$650	389	$550	465	$745	690	$678	500	$1,765	1238	$1,110	1145

If, for example, management wants to increase maturity from the current value of 0.48 (Technology Development stage) to 0.69 (Engineering & Manufacturing Development stage), using a maximum of 40% of the remaining time (7,649 labor-hours), the PSDA cost minimization model calculated a minimum additional development cost of $5.914 million and would require 3,797 labor-hours.

In addition, the development plan that can achieve this desired SRL value of 0.69 with the least cost will be attained if the subsystems that are based on each technology element reach the maturity levels listed in Table 6. The latter shows that of the six subsystems, two are ahead ($SRL_{1,3,}$), two are behind ($SRL_{4,5}$) and two are close to the same level ($SRL_{2,6}$) as the whole system. This insight can become useful when the maturity levels are associated with systems engineering activities. That is, the spectrum of SRL_i's can indicate levels of variation in the systems engineering activities, which are needed to mature the entire system.

Table 6. Subsystem and Composite SRLs

SRL1	SRL2	SRL3	SRL4	SRL5	SRL6	∑	Composite SRL = ∑/6
0.856	0.707	0.815	0.461	0.593	0.722	4.154	0.692

Table 7 summarizes the additional results for the targeted SRL values and Table 9 indicates the development plan for each improvement scenario.

Table 7. Best Solutions for Desired SRL Values

Year	SRL		Time (man-hrs)		Computed Minimum Cost ($ x1000)
	Targeted	Computed	Targeted	Computed	
1	0.48	0.48	NA	NA	NA
2	0.58	0.587	3,824	1,654	2,203
3	0.69	0.692	7,649	3,797	5,914
4	0.79	0.794	11,473	7,667	11,065
5	0.89	0.896	15,298	11,309	16,888
6	1.00	1.00	19,122	19,122	26,574

Table 8. Development Plan

Year	Target SRL	TRL						IRL						
		1	2	3	4	5	6	1,2	1,3	2,3	2,4	3,5	4,5	5,6
6	1.000	9	9	9	9	9	9	9	9	9	9	9	9	9
5	0.89	9	9	9	8	9	9	9	9	9	8	8	5	7
4	0.79	8	9	9	6	9	9	9	9	9	5	8	4	6
3	0.69	8	8	9	6	9	9	8	8	7	5	7	2	4
2	0.58	8	8	8	6	7	6	7	7	7	5	6	2	4
1	0.48	8	8	7	6	6	6	5	6	6	5	6	2	2

It must be noted that the algorithm can only work if the management objectives are inherently feasible. If a prescribed objective is impossible to achieve—as when too little time or labor-hours are available—the algorithm will not produce a solution.

3.3 First-to-Market/Deployment Strategy

A very similar optimization procedure can be designed to determine how fast a system can reach a certain stage in the development lifecycle or how quickly it can be deployed. In this case, there may be a need to launch an experimental system in favor of maximum current and short-term effectiveness while disregarding long-term reliability. The objective may be to meet pressing needs in a war theater or commercial market as quickly as possible.

For example, there is currently a necessity to deliver Operationally Responsive Space (ORS) systems to meet shortfalls in tactical space capabilities (e.g., communications and imagery) that the warfighter needs in Iraq and Afghanistan. These are being satisfied through the development of small experimental satellites called TacSats (average cost=$87 million) as well as improvements in the capabilities of small launch vehicles (GAO, 2008). In the private sector, the first company to develop commercially viable autonomous-recharging powertrain battery systems will enjoy first-mover advantages in the defense and commercial motor vehicle industry. Such a company will be able to create and sustain barriers to entry through control of the technology (property rights), brand recognition and so on.

In such instances, the primary objective is to maximize the readiness of the system utilizing a given amount of limited resources. Sauser and Ramirez-Marquez (2009) developed an SRL maximization model—SRL_{max}—for such an application. As with the SCOD_{min} model, this model recognizes that the technologies as well as the integration elements that form the system compete for resources and that in order to reach the highest level of readiness, a program manager must be able to allocate the limited resources optimally. Just as what had to be done in the SCOD_{min} model, the program manager must be able to decide which technologies and integrations can be advanced to which levels of readiness at a certain point in time in order to reach the highest level of readiness for the system. The general mathematical form of SRL_{max} follows:

Maximize: SRL ($\mathbf{TRL,IRL}$)

Subject to: R_1 ($\mathbf{TRL,IRL}$) $\leq r_1$

.

.

.

R_h ($\mathbf{TRL,IRL}$) $\leq r_h$

As with the minimization model above, SRL_{max} belongs to the class of integer-valued, non-linear problems.

Using the same data for the notional example above, the maximization algorithm indicated that to get to the Engineering & Manufacturing Development phase of the lifecycle with an SRL value of 0.73, $7.724 million and 5,081 labor-hours will be required. For comparison purposes, the optimal development plans to get to the Engineering & Manufacturing Development stage, albeit at different SRL values (0.69 for cost minimization and 0.73 for SRL maximization) are presented in Table 9 below.

Table 9. Comparable Development Plans

Model	SRL	TRL						IRL						
		1	2	3	4	5	6	1,2	1,3	2,3	2,4	3,5	4,5	5,6
SCOD_{min}	0.69	8	***8***	9	6	9	9	8	8	***7***	5	7	2	***4***
SRL_{max}	0.73	8	***9***	9	6	9	9	8	8	***8***	5	7	2	***5***

The cost minimization strategy will reach this stage by year 3. On the other hand, when the objective is to deploy as quickly as possible, the system can be in production as soon as the prescribed resources are applied, provided the process and product technologies are amenable to accelerating the schedule. This assumes constant productivity that represents an ideal situation. In reality, there is more likely to be “process congestion,” which can lead to increased coordination and communication expenses, among other things. Therefore, for the maximization model, the estimated incremental costs for each TRL and IRL level must be adjusted upwards in order to reflect the cost implications of “crashing” the schedule. Depending upon these CTE- and integration link-specific cost increases, the formulated development plan is likely to be different from the one obtained from the minimization model.

The results must be carefully examined by the program manager and adjusted according to a proper understanding of the technologies involved and the context for the system. For example, in the previous illustration, some of the integration links have to be examined more closely and compared to a pre-determined minimum acceptable readiness values. If the minimum IRL values of, say, 5 are required in order to proceed to production within acceptable risk limits, then, additional resources must be allocated to mature integration links (4,5) and (5,6) to this level. This threshold IRL value may be higher for a cost minimization strategy (whereas long-term reliability is an important lifecycle variable) and lower for the first-to-deployment experimental strategy that characterizes the TacSats program in which long-term reliability is not quite as important as delivering the capability sooner rather than later.

It must also be noted that the solution is driven by the estimates of cost and labor inputs. The effectiveness of the optimization models are very dependent on the accuracy of the estimates of the resources required to proceed from one readiness level to the next. If these values are unrealistic, sub-optimal solutions will be generated.

Furthermore, given the high levels of uncertainty associated with complex systems that are under development, estimates of costs which are farther into the future may be less reliable than those which are closer to the current period. Thus, estimates have to be continually refined and reapplied to the optimization algorithm in order to fine-tune the development plan accordingly.

4. Monitoring Progress

The metrics that measure readiness together with the development plans generated by the appropriate optimization model serve as the foundation for a mechanism that can measure and communicate accomplishments during the development of complex systems. As a general principle, EVM may be retained as the preferred tool for project managers tasked with developing each of the critical technology and integration elements. To consider all the projects that an enterprise has to manage, Project Portfolio Management (PPM) has been suggested by De Reyck et al. (2005) and Martinsuo and Lehtonen (2007). In between, to manage the development of a system, which is a set of projects that are related because they share a common objective or client—a program management tool is required. Developing such a tool, which we refer to as System Earned Readiness Management (SERM), is one of the activities we intend to pursue next. SERM is intended to be very similar to EVM. It must answer the following questions:

- What amount of readiness is expected from the tasks planned?
- What level of readiness was accomplished by the tasks completed?
- How many resources did the accomplished level of readiness cost?

- How many resources were allocated to reach this level of readiness?
- What was the total budgeted resources to fully mature the system?
- What are now the expected total resources required to develop the system?

4.1 Work Breakdown Structure for SERM

SERM will require a breakdown of the tasks necessary to define the system, develop the critical technology elements and integrate them into the desired system. The tasks could be oriented towards the phases of the system lifecycle at the highest levels (i.e., Materiel Solution Analysis, Technology Development, Engineering & Manufacturing Development, Production & Deployment, and Operations/Support) and continue to be disaggregated into the TRL and IRL levels that have to be attained and, if necessary, down to the jobs that must be completed to reach the desired readiness for each time period. An abbreviated example is shown in Table 10 below.

Table 10. WBS for SERM

1. SYSTEM A 1.1Materiel Solution Analysis Phase 1.1.1 Materiel Solution Analysis Decision Review 1.1.1.1 Joint Requirements Oversight Council (JROC) recommendations 1.1.1.2 Initial Capabilities Document(ICD) 1.1.1.2.1 Preliminary concept of operations 1.1.1.2.2 Description of needed capability 1.1.1.3 Analysis of Alternatives (AoA) 1.1.1.3.1 Determine acquisition phase of entry 1.1.1.3.2 Identify the initial review milestone 1.1.1.3.3 Designate the lead DoD Component(s) 1.1.1.3.4 Prepare Acquisition Decision Memorandum 1.1.2 Satisfy phase-specific entrance criteria for initial review milestone 1.1.2.1 Proposed materiel solution 1.1.2.2 Secure full funding for Technology Development Phase
1.2. Technology Development Phase 1.2.1 Management 1.2.1Materiel solution 1.2.2Technology/system development strategy 1.2.3 Acquisition decision memorandum 1.2.2 CTE 1 1.2.2.1 TRL =3 1.2.2.2 TRL =4 1.2.2.3 TRL =5 1.2.3 CTE 2 1.2.3.1 TRL =3 1.2.3.2 TRL =4 1.2.3.3 TRL =5 1.2.3.4 TRL =6 1.2.x CTE n……etc.
1.3. Engineering & Manufacturing Phase 1.3.1 Management 1.3.1.1 Key performance parameters … etc. 1.3.2 CTE 1 1.3.2.1 TRL = 6 ... etc
1.4. Production & Deployment Phase
1.5. Operations & Support Phase

4.2 Determining Earned Readiness and Baseline

A readiness-oriented baseline should reflect the cumulative increase in the readiness of the technology and integration elements of the system. Readiness is allocated throughout the system by assigning the TRL and IRL values to the tasks completed *if and only if* they satisfy the definition for that readiness level. Thus, it is possible that under SERM, a planned task may be completed during the specified time frame but if it fails to advance the maturity of that particular technology or integration link, that completed task did not earn any readiness values. By doing this, a program manager can clearly see which activities have failed, in order to identify the sources of cost overruns and find and communicate explanations for exceeding the budget.

This scenario is not unlikely given the high amount of uncertainty involved with developing complex systems. This uncertainty—the result of novelty, high technological content and very long development lifecycles—can lead to late identification of requirements and design flaws, requirements churn (due to inaccurate statements of user needs), delays in integration and testing and the need for significant unplanned work—rework as well as revisions in the system architecture and technology choices (Brownsword & Smith, 2005).

5. Conclusion

This paper suggested the development of a new program assessment and evaluation system that relies on the readiness measurement of a system's critical technology elements (using TRL) and the integrations that link them to each other (using IRL), which are then combined to estimate a System Readiness Level (SRL) in order to determine the readiness of the system as a whole. SRL can then be combined with the prescribed strategy for developing the system (either minimize costs or be the first to deploy the system) and used in an appropriate constrained optimization model to formulate the optimal development plan. Based on this plan, the progress of the system development effort can be monitored and evaluated using System Earned Readiness Management (SERM).

Of the various concepts enumerated here, only TRL has been accepted as a generally valid principle. IRL, SRL and SERM are all new, and thus require substantial efforts to verify and validate. It is necessary to apply them to a sufficient number of programs that have recently been completed or are currently being implemented. It must be noted that EVM for project management became more widely accepted only when the graduate students in the DoD's academic institutions were able to apply it to defense acquisition projects and show its benefits (Abba, 2001). The early anecdotal evidence from the few attempts to apply SRL has been positive and may justify a similar approach to verify and validate it.

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