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A Systems Approach to Expanding the Technology Readiness Level within Defense Acquisition

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Abstract

This paper proposes the use of a new Systems Readiness Level (SRL) scale for managing system development and for making effective and efficient decisions during the defense acquisition process. This scale incorporates both the current Technology Readiness Level (TRL) of the Department of Defense (DoD) and the concept of an Integration Readiness Level (IRL) developed by Stevens Institute of Technology. The paper describes the foundations for the SRL and how it is formulated; it also demonstrates the SRL's application within the defense acquisition process using a sample case with notional readiness values.

Keywords: acquisition, technology readiness level (TRL), integration readiness level (IRL), technology readiness assessment, system readiness level (SRL)

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1. Introduction

In 1999, the United States (US) General Accounting Office (GAO)[1] stated that there were few metrics used within the US Department of Defense (DoD) to gauge the impact of investments or the effectiveness of processes used to develop and transition technologies. It asserted that additional metrics in technology transition were needed (GAO, 1999). In 2002, in a testimony before the Subcommittee on Readiness and Management Support, Committee on Armed Services of the US Senate, the GAO further explained DoD challenges in implementing best practices; it suggested the DoD needed to enable success through the demonstration of value and the credibility of new processes through the use of metrics (GAO, 2002).

To address these compounding challenges, in 1999, the DoD began implementing the Technology Readiness Level (TRL) as a metric to assess the maturity of a program's technologies before its system development begins (DoD, 2005a; 2005b). Additionally, the DoD made constructive changes to its approaches to acquisition that would address these issues by 2001: (1) assuring a weapon systems' technologies are demonstrated to a high level of maturity before beginning its program and (2) using an evolutionary or phased approach to developing such systems (GAO, 2002).

Even with the implementation of new processes and practices within DoD acquisition, the challenges are still significant (e.g., over the next five years, the DoD plans to invest an estimated $900 billion to develop and procure weapons systems at a pace that far exceeds the availability of resources (GAO, 2008)).

Consequently, despite the utility and value of the TRL as a metric for determining technology maturity before transitioning into a system, we contend that TRLs were not intended to address systems integration nor to indicate that the technology will result in successful development of a system (Gove, 2007; Mandelbaum, 2007; 2008). As Baines (2004) describes, "the wrong technology, or even the right technology poorly implemented, can be disastrous" (p. 447. Therefore, in this paper we will build upon a concept originally proposed by Sauser, Verma, Ramirez-Marquez and Gove (2006) for the development of a System Readiness Level (SRL) scale that incorporates the maturity level of the critical components and the interoperability of the entire system. A fundamental argument to this approach is that the metrics for the coupling and maturation of multiple technologies and systems have been shown to be unresolved issues of strategic relevance (Nambisan, 2002; Watts & Porter, 2003). In addition, component-level considerations relating to integration, interoperability, and sustainment become equally or more important from a systems perspective during acquisition (Sandborn, Herald, Houston & Singh, 2003).

The SRL we will describe and demonstrate is a function and scale that incorporates the current TRL scale along with a scale of integration. The combination for utilization of the SRL we contend aids in making strategic decisions during defense acquisition. The resultant SRL scale

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[1] This agency became the US Government Accountability Office on July 7, 2004.

can provide an assessment of overall system development and can identify potential areas that require further work to facilitate prioritization. This new SRL scale of system maturity can be used with decision-making tools for the potential acquisition of systems—which involve the dependency and interplay among performance, availability (reliability, maintainability, and supportability), process efficiency (system operations, maintenance, and logistics support), and system lifecycle cost.

2. Theoretical Foundation

In program management, resources are frequently allocated with the purpose of executing tasks to maintain schedule and budget. This can lead to an assignment-type program scheduling problem (Salewski, Schirmer & Drexl, 1997) when the ultimate objective of any program is to realize a product (or system) to satisfy a customer. A fundamental challenge to resolving this problem is that when attempting to meet the emergent needs of the warfighter, program managers (PMs) will often continue development of a system through the acquisition lifecycle— while they coordinate the design activities with preliminary, ambiguous, or subjective information (Pich, Loch & De Meyer, 2002). The balance between customer needs (e.g., warfighter) and design activities creates a tension between the overview required by the program manager and the detail that is the focus of the system developers (de Haes, 2006). To find a concession, organizations have relied on subjective assessment techniques for developing the program overview, which then becomes the basis for making strategic acquisition decisions. However, these subjective assessments are human-intensive, error-prone, and inadequate for the desired management controls; such controls should be based on system attributes that can be quantitatively measured using system metrics (Yacoub & Ammar, 2002). The tension between subjectivity and detail is rationalized through prescriptive techniques—which allow people to make better decisions by using normative models, but with knowledge of the limitations and descriptive realities of human judgment (Smith & Winterfeldt, 2004).

Within agencies of the US government, the prescriptive tool and soft metric of the TRL has been used as an assessment of the maturity of evolving technologies prior to incorporating them into a system or sub-system. The original TRL was a bi-product of the National Aeronautics and Space Administration's (NASA) post-Apollo era as ontology for contracting support (Sadin, Povinelli & Rosen, 1989). In the last nine years, other government agencies and contractors have adopted the TRL scale with specific variations to satisfy their needs (e.g., the Department of Defense (DoD), the Department of Energy (DoE), the National Air and Space Intelligence Center).

There have been many attempts to identify alternative readiness/maturity levels that will complement the TRL, such as Design Readiness Level, Manufacturing Readiness Level, Software Readiness Level, Operational Readiness Level, Human Readiness Level, Habitation Readiness Level and Capability Readiness Levels (Bilbro, 2007; Connelly, Daues, Howard & Toups, 2006; Cundiff, 2003). Unfortunately, each has faltered in addressing the core issue with the TRL as identified in recent literature; thus, the legacy constraints with the TRL's abstraction have remained. These constraints are: (1) the inability to represent integration between technologies, (2) an uncertainty in the maturation of technologies, and (3) an inability to compare the impact of alternative TRLs on the system as a whole (Cundiff, 2003; Dowling & Pardoe,

2005; Mankins, 2002; Meystel, Albus, Messina & Leedom, 2003; Moorehouse, 2001; Shishko, Ebbeler & Fox, 2003; Smith, 2005; Valerdi & Kohl, 2004).

Based on these fundamental conjectures, a more comprehensive set of concerns becomes relevant when the TRL is amplified from the level of an individual technology to a system context that involves the interplay of multiple technologies. For example, in NASA's Mars Climate Orbiter, the failure of two—independently evaluated—technologies to use the same units (i.e., Metric versus English) contributed to the loss of the spacecraft. While testing is absolutely necessary, it is not always capable of catching the many small errors that can occur when two different components of software and/or hardware exchange data in a raw format. If the integration of two pieces of technology followed some sort of maturation process, just as the technology itself does, this would provide an assessment of integration readiness and a direction for improving maturity from a systems context during the development process. Not withstanding the previously identified limitations of the TRL, any metric, as described by Dowling and Pardoe (2005), should not lose sight of what makes it effective and efficient in an organization:

1. The way the value is used should be clear.
2. The data to be collected for the metric should be easily understood and easy to collect.
3. The method of deriving the value from the data should be clear and as simple as possible.
4. Those for whom the use of the metric implies additional cost should see as much direct benefit as possible (i.e., collecting the data should not cost more than its value to the decision process).

3. Development of a System Readiness Level

In theory, technology and system development follow similar evolution (or maturation) paths; a technology is inserted into a system (e.g., evolutionary acquisition) based on its maturity, functionality and environmental readiness and ability to interoperate with the intended system. However, many of the factors that may determine the successful deployment of a system into its operational environment are not always effectively implemented during the developmental lifecycle (Parsons, 2006). Fundamentally, any system under development is composed of core technology components and their linkages in accordance with the proposed architecture. Henderson and Clark (1990) showed that the distinction between the relationships of the components and the system architecture requires two types of knowledge: component knowledge and architectural knowledge (i.e., knowledge on how the components are integrated). These researchers emphasized that systems often fail because attention is given to the technology while knowledge of the linkages/integrations is overlooked. They explain that improper attention to the linkages/integrations has an impact on the systems' technical evolution, organizational experience, recurrent task, and technical knowledge as they relate to the component linkages. It also influences the product architecture, communication channels, and problem solving strategies. Therefore, while the TRL provides the metric for describing component knowledge, based on Henderson and Clark, one would still be interested in a metric that provides a description of architectural knowledge or integration. In addition, using modeling and simulation, Ford and Dillard (2008) were able to demonstrate the inherent value of integration to

the success of evolutionary acquisition. They were able to demonstrate the relative impact of making integrations decisions late in the acquisition lifecycle.

While there have been some efforts to develop metrics that can be used to evaluate integration (e.g., DoD, 1998, March 30; Mankins, 2002; Fang, Hu & Han, 2004; Nilsson, Nordhagen & Oftedal, 1990), there is a need for a metric that can be used with the TRL to effectively determine a system maturity. This paper addresses this need by developing a system maturity scale that incorporates the TRL and a metric of integration maturity, which is described below.

3.1.   Integration Readiness Level

The application of ontology metrics to support integration has been extensively used in the computer industry to define the coupling of components (Orme, Yao & Etzkorn 2006; 2007), but a common ontological approach to technology integration for system development has been far less developed. One of the first attempts to address this was conducted by Mankins (2002) when he proposed an Integrated Technology Analysis Methodology to estimate an Integrated Technology Index (ITI). The ITI was then used for a comparative ranking of competing advanced systems. The study brought to the forefront the difficulty of progressing through the TRL scale and choosing between competing alternative technologies. It did not adequately address the integration aspects of systems development. Based on concerns for successful insertion of technologies into a system, the Ministry of Defence in the United Kingdom developed a Technology Insertion Metric that includes, among other things, an Integration Maturity Level (Dowling & Pardoe, 2005). Building upon these efforts, Gove (2007) and Gove, Sauser and Ramirez-Marquez (2007) performed a review of aerospace and defense-related literature to identify the requirements for developing a 7-level integration metric that they called Integration Readiness Level (IRL). These factors led to the definition of the requirements for an integration metric, which are to:

1. Provide an integration-specific metric, to determine the integration maturity between two or more configuration items, components, and/or subsystems.
2. Provide a means to reduce the uncertainty involved in maturing and integrating a technology into a system.
3. Provide the ability to meet system requirements during the integration assessment so as to reduce the integration of obsolete technology over less mature technology.
4. Provide a common platform for both new system development and technology insertion maturity assessment.

Using these requirements, Gove et al. (2007) assessed Mankin's Integrated Technology Index (2002), Nilsson et al.'s integration metric (1990), Fang et al.'s Interoperability Assessment Model (2004), and their 7-level IRL (Sauser et al., 2006). While none of these methods met all the stated requirements, the analysis yielded a modified 9-level IRL which did. The resulting IRL is a systematic analysis of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points (i.e., TRLs) and is described in Table 1.

Gove et al. (2007) also evaluated these integration maturity metrics with multiple system case studies (i.e., Mars Climate Orbiter, Ariane 5, two Hubble Space Telescope cases) to determine

how effective they would be in recognizing integration risks in development. The case study analysis showed that the existing approaches to integration metrics would not have identified the root cause of the development risks. Application of the IRL approach, however, was shown to have highlighted low levels of integration maturity and identified specific areas of development needing further management and engineering attention. Consequently, we use this IRL in the development of the SRL.

Table 1. Integration Readiness Levels
(Gove, 2007; Gove et al., 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 the TRL 9, it must first be integrated into the system and then proven in the relevant environment; thus, progressing IRL to 9 also implies maturing the component technology to the 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, to label units of measure 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 to communicate interpretable data. IRL 3 represents the first tangible step in the maturity process.
2	There is some level of specificity to characterize the **Interaction** (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	This is the lowest level of integration readiness and describes the selection of a medium for integration.

	detail to allow characterization of the relationship.	

3.2. System Readiness Level

The introduction of an IRL to the assessment process not only provides a check as to where the technology is on an integration readiness scale but also presents a direction for improving integration with other technologies. Just as a TRL has been used to assess the risk associated with developing technologies, an IRL is designed to assess the risk associated with integrating these technologies. Now that both the technologies and integration elements can be assessed and mapped along a numerical scale, the next challenge is to develop a metric that can assess the maturity of the entire system that is under development. Sauser, Ramirez-Marquez, Henry and DiMarzio (2008) were able to demonstrate how the TRLs and IRLs for any system under development can yield a measure of system maturity called a System Readiness Level (SRL). The rationale behind the SRL developed by Sauser et al. (2008) is that in the development lifecycle, one would be interested in addressing the following considerations:

- Quantifying how a specific technology is being integrated with every other technology to develop the system.

- Providing a system-wide measurement of readiness.

The computational approach for the SRL has been considered as a normalized matrix of pair-wise comparisons of the TRLs and IRLs. The SRL matrix consists of one element for each of the constituent technologies and, from an integration perspective, quantifies the readiness level of a specific technology with respect to every other technology in the system. It should be mentioned that although the original (1,9) scale for both the TRL and IRL can be used, the use of normalized values allows for a more accurate assessment when comparing the use of competing technologies. Thus, the values used in the matrices [TRL] and [IRL] are normalized (0,1) from the original (1,9) levels by dividing each element by 9.

In addition, when no integration is present between two technologies, an IRL value of 0 is assigned. This is in contrast to using a value of 9 when no integration is present, as was originally proposed by Sauser et al. (2008). Using the higher value of 9 gave excessive weight to the IRL and was distorting the overall SRL value upwards. Consequently, this means that in the future, if the architecture is changed such that those two technologies become integrated, one can go back and apply the corresponding IRL value of that new integration link. For integrations to itself, a non-normalized IRL value of 9 or normalized value of 1 is used. The reason for this has a philosophical underpinning. In the view of one's self, it is a matter of a person integrating various parts of their personality into a harmonious, intact whole with the purpose of keeping the self intact and uncorrupted. For this reason, when interpreting the integration of a technology to itself, we define it as uncorrupted (i.e., fully mature). If we were to consider the integrations within the technology independent of the other technologies, then we would be calculating a different SRL and, thus, be considering a different system independent of the system of interest.

3.3. Calculating the SRL

The computation of the SRL is a function of the TRL and IRL matrices:

- Matrix **TRL** provides a blueprint of the state of the system with respect to the readiness of its technologies. **TRL,** defined as a vector with n entries, is defined in Equation 1, where TRL_i is the TRL of technology i.

$$(1) \qquad [TRL]_{n \times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ ... \\ TRL_n \end{bmatrix}$$

- Matrix **IRL** illustrates how the different technologies are integrated with each other from a system perspective. For a system with n technologies, [IRL] is defined in Equation 2, where IRL_{ij} is the IRL between technologies i and j. The hypothetical integration of a technology i to itself is denoted by IRL_{ii}.

$$(2) \qquad [IRL]_{n \times n} = \begin{bmatrix} IRL_{11} & IRL_{12} & ... & IRL_{1n} \\ IRL_{21} & IRL_{22} & ... & IRL_{2n} \\ ... & ... & ... & ... \\ IRL_{n1} & IRL_{n2} & ... & IRL_{nn} \end{bmatrix}$$

In these matrices, the standard TRL and IRL levels corresponding to values from 1 through 9 should be normalized. A normalized value of 1 for element IRL_{ij} can be understood as one of the following with respect to the ith and jth technologies: 1) they are completely compatible within the total system; 2) they do not interfere with each other's functions; 3) they require no modification of the individual technologies; and 4) they require no further integration linkage development.

In any system, each of the constituent technologies is connected to a minimum of one other technology through a bi-directional integration. The way each technology is integrated with other technologies is used to formulate an equation for calculating SRL. This SRL equation consists of the TRL and IRL values of the technologies and the interactions that form the system. In order to calculate a value of the SRL from the TRL and IRL values, we propose a normalized matrix of pair-wise comparison of the TRL and IRL values.

Based on these two matrices, an SRL matrix is acquired by obtaining the product of the TRL and IRL matrices, as shown in Equation 3.

$$(3) \qquad [SRL]_{n \times 1} = [IRL]_{n \times n} \times [TRL]_{n \times 1}$$

The SRL matrix consists of one element for each of the constituent technologies and, from an integration perspective, quantifies the readiness level of a specific technology with respect to every other technology in the system while also accounting for the development state of each

technology through the TRL. Mathematically, for a system with n technologies, [SRL] is as shown in Equation 4.

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

The representation of each of the SRL values obtained in Equation 4 addresses the first consideration previously discussed in Section 3.2. Note that these values would fall within the interval (0,n); so, for consistency, for each technology, say i, its corresponding SRL_i is divided by ni (ni being the number of integrations of technology i, with every other technology as dictated by the system architecture—including its integration to itself) to obtain its normalized value between (0,1). The SRL for the complete system is the average of all such normalized SRL values, as shown in Equation 5. Equal weights are given to each technology, since they are each identified as critical technology elements; in this way, a simple average is estimated. A standard deviation can also be calculated to indicate the variation in the system maturity and parity in subsystem development.

$$
(5) \quad SRL = \frac{\dfrac{SRL_1}{n_1} + \dfrac{SRL_2}{n_2} + ... + \dfrac{SRL_n}{n_n}}{n}
$$

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

The SRL metric can be used to determine the maturity of a system and its status within a developmental lifecycle. Table 2 presents an example of how the various levels of the SRL scale can correlate to an acquisition lifecycle (DoD, 2005a). The ranges of SRL represented in Table 2 are derived from sensitivity analysis with sample systems. While we are working to verify and validate this correlation as part of current research, we contend that any correlation should be accessed based unique organizational and system development environments. Also, it is important to note that in this correlation, a system that has not reached full maturity is capable of transitioning into a Production phase. This is predicated on the reasoning that most systems are deployed without all of the technologies and integrations having reached full maturity. For example, many military and space systems cannot be verified in their operational environment until deployed; likewise, many systems are part of an evolutionary lifecycle in which the final maturity will be verified once deployed or in the next evolution.

Table 2. System Readiness Levels

SRL	Acquisition Phase	Definitions
0.90 to 1.00	*Operations & Support*	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total lifecycle.
0.80 to 0.89	*Production*	Achieve operational capability that satisfies mission needs.
0.60 to 0.79	*System Development & Demonstration*	Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; reduce 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 appropriate set of technologies to integrate into a full system.
0.10 to 0.39	*Concept Refinement*	Refine initial concept; develop system/technology strategy.

NOTE: These ranges have been derived from sensitivity analysis with sample systems. They are currently undergoing field verification and validation under Naval Postgraduate School Contract # N00244-08-0005.

4. Example of SRL Calculation

To show the steps and analysis involved in formulating the SRL, the following example will use notional data (with TRLs that range from a low of 6 to a high of 9 and IRLs ranging from 5 to 9) from a system currently under development for a family of surface ships in the US Navy. The system architecture analyzed (see Figure 1) represents an end-to-end integration of command-and-control capabilities with a variety of unmanned vehicles and intelligence, surveillance, and reconnaissance sensor packages. These elements are capable of autonomous operations and include both off-the-shelf equipment and cutting-edge new development networked seamlessly together to enhance effectiveness and efficiency. For this system, the following matrices can be created for the TRL and IRL (Equations 1 and 2).
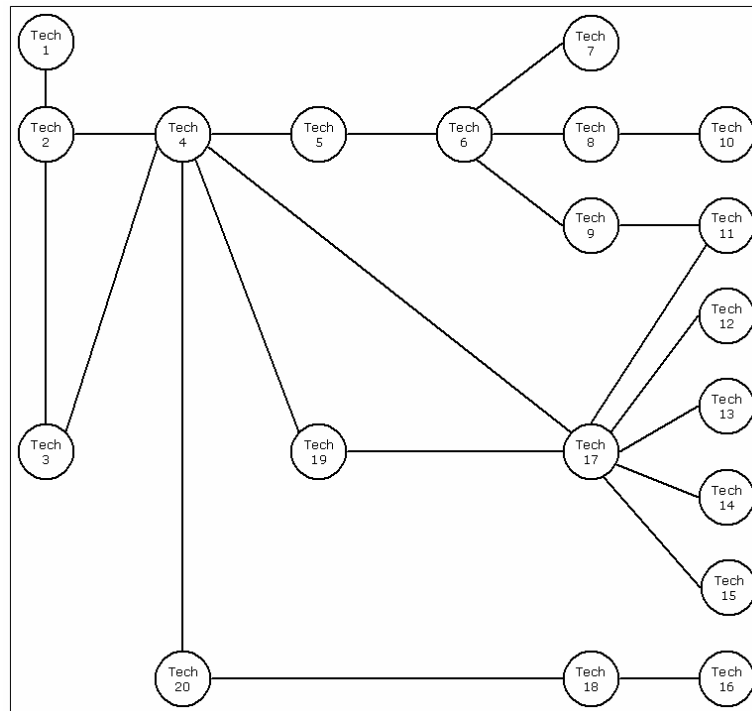
Figure 1. Schematic Architecture of System X

(1)

$$[TRL]_{20\times1} = \begin{vmatrix} TRL_1 \\ TRL_2 \\ \dots \\ TRL_{20} \end{vmatrix} = [9 \quad 9 \quad 9 \quad 7 \quad 6 \quad 9 \quad 9 \quad 7 \quad 6 \quad 9 \quad 9 \quad 8 \quad 7 \quad 6 \quad 8 \quad 7 \quad 6 \quad 8 \quad 9 \quad 9]^T$$

$$[IRL]_{20\times20} = \begin{bmatrix} IRL_{11} & IRL_{12} & ... & IRL_{1n} \\ IRL_{21} & IRL_{22} & ... & IRL_{2n} \\ ... & ... & ... & ... \\ IRL_{n1} & IRL_{n2} & ... & IRL_{nn} \end{bmatrix}$$

$$= \begin{bmatrix}
9 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
9 & 9 & 9 & 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 9 & 9 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 8 & 7 & 9 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 5 & 6 \\
0 & 0 & 0 & 6 & 9 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 7 & 9 & 9 & 8 & 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 9 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 8 & 0 & 9 & 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 7 & 0 & 0 & 9 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 6 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 9 & 0 & 0 & 0 & 0 & 0 & 5 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 0 & 9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 0 & 9 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 8 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 8 & 0 & 0 \\
0 & 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 5 & 9 & 9 & 9 & 8 & 0 & 9 & 0 & 9 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 8 & 0 & 9 & 0 & 7 \\
0 & 0 & 0 & 5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 9 & 0 & 9 & 0 \\
0 & 0 & 0 & 6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 7 & 0 & 9
\end{bmatrix}$$

(2)

As indicated in the above integration matrix, we assign an IRL value of 0 when there is no integration link contemplated between any two technologies. For integration to itself, an IRL value of 9 is used. Next, we normalize the [TRL] and [IRL] matrices by dividing each element by 9. Then, we calculate [SRL] as follows (Equation 3 and 4):

(3 and 4) $\quad [SRL] = [IRL]_{20\times20}[TRL]_{20\times1} = \begin{bmatrix} SRL_1 \\ SRL_2 \\ ... \\ SRL_{20} \end{bmatrix}$

Table 3 indicates the calculated values for each SRL_i.

Table 3. Individual SRL Values

	SRL_1	SRL_2	SRL_3	SRL_4	SRL_5	SRL_6	SRL_7	SRL_8	SRL_9	SRL_{10}
$(0, n_i)$	2.000	3.691	2.605	4.482	1.963	3.728	2.000	2.333	2.000	1.519
$(0,1)$	1.000	0.923	0.868	0.640	0.654	0.746	1.000	0.778	0.667	0.759
	SRL_{11}	SRL_{12}	SRL_{13}	SRL_{14}	SRL_{15}	SRL_{16}	SRL_{17}	SRL_{18}	SRL_{19}	SRL_{20}
$(0, n_i)$	1.741	1.556	1.444	1.333	1.482	1.568	5.778	2.358	2.099	2.210
$(0,1)$	0.580	0.778	0.722	0.667	0.741	0.784	0.722	0.786	0.699	0.737

The calculated Composite SRL scale (Equation 5) of 0.76 indicates that the system under development should be in the System Development and Demonstration phase (also see Figure 2).

$$(5)\ Composite\ \ SRL = \frac{\dfrac{SRL_1}{n_1} + \dfrac{SRL_2}{n_2} + ... + \dfrac{SRL_n}{n_n}}{n} = \frac{\dfrac{SRL_1}{2} + \dfrac{SRL_2}{4} + ... + \dfrac{SRL_{20}}{3}}{20} = 0.76$$

Aside from the SRL providing an assessment of overall system development, it can also be a guide in prioritizing potential areas that require further development. That is, if we are considering a "systems-focused approach" to our methodology, then we cannot evaluate a system based on just a single number, such as the Composite SRL. As shown in our example and illustrated by Figure 2, the SRL_is (technologies with their integration links considered) present a spectrum showing some subsystems whose readiness levels (i.e., SRL_i) are in the three development phases other than the Composite SRL's System Development and Demonstration phase. While it could be argued that the overall SRL is only as good as the lowest SRL_i, this perspective would also lose sight of even those technologies that are potentially developing faster than the system (see $SRL_{1,2,3,7}$). In understanding the value of the SRL analysis, we must understand the spectrum of SRL_i and its relationship to the Composite SRL (see Figures 2 and 4). For example, the value of considering the IRL with the TRL is seen in Technology 11. This technology has a TRL of 9. However, when we consider its IRLs (both of which are only in level 5), we can determine it not only is less mature but is a phase behind the Composite SRL. This means that this subsystem (SRL_{11}) is still in the Technology Development phase, while the overall system is already in the System Development and Demonstration phase. In addition, as shown in Figure 2, 20% of the technologies are at least one phase ahead.

Ideally, this type of analysis can facilitate strategic decisions about incremental technology and integration investments of limited resources. For example, in the upcoming budgetary period or fiscal year, resources may be shifted in favor of accelerating the development of the technologies and integration links that are behind and temporarily away from those that are ahead—provided such a shift is technologically and organizationally feasible. This capability can become important when a specific technology is a conduit for downstream technologies—its maturity is critical for the system to reach a certain level of maturity. For example, the system diagram in Figure 1 shows that Technology 4 is such a technology. If the systems engineer has specified that at this particular time period, the SRL for this subsystem must be at least 0.80 before the rest of the technologies can be developed further, the program manager will know that the TRL and IRL for Technology 4 have to be improved to raise its SRL from the current value of 0.64.
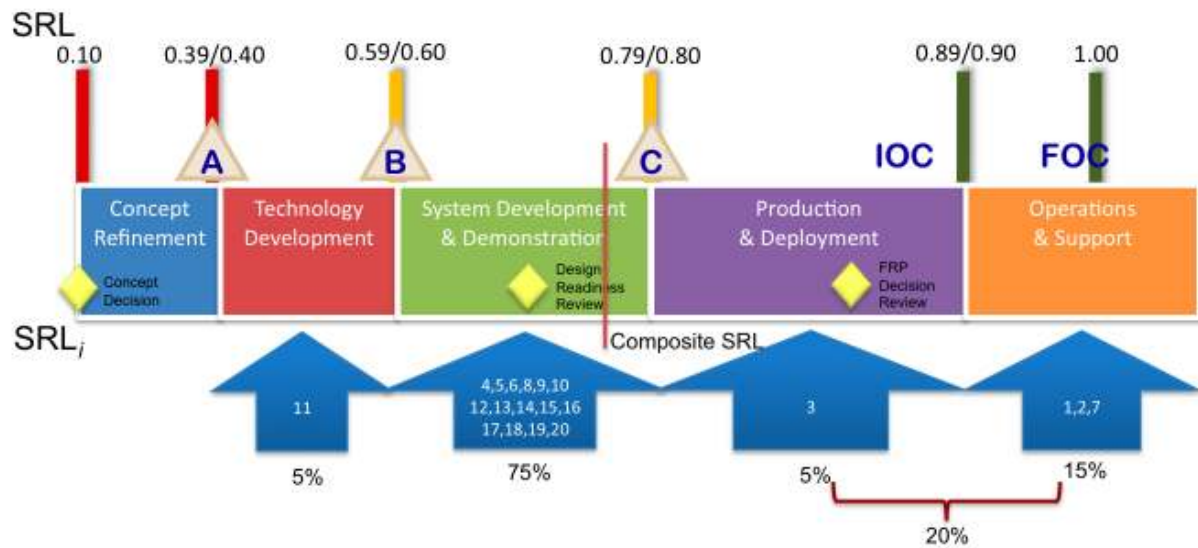
Figure 2. SRL Mapping to Defense Acquisition

5. SRL Relevance and Future Research

Given the ability to estimate readiness of a system under development (summarized in Figure 3), organizations can systematically evaluate the implications of using alternative technologies or system architectures, prepare development plans that optimize the objectives of the development team, and eventually be able to evaluate and monitor the progress of the development effort to identify problem areas and corrective measures (example in Figure 4).
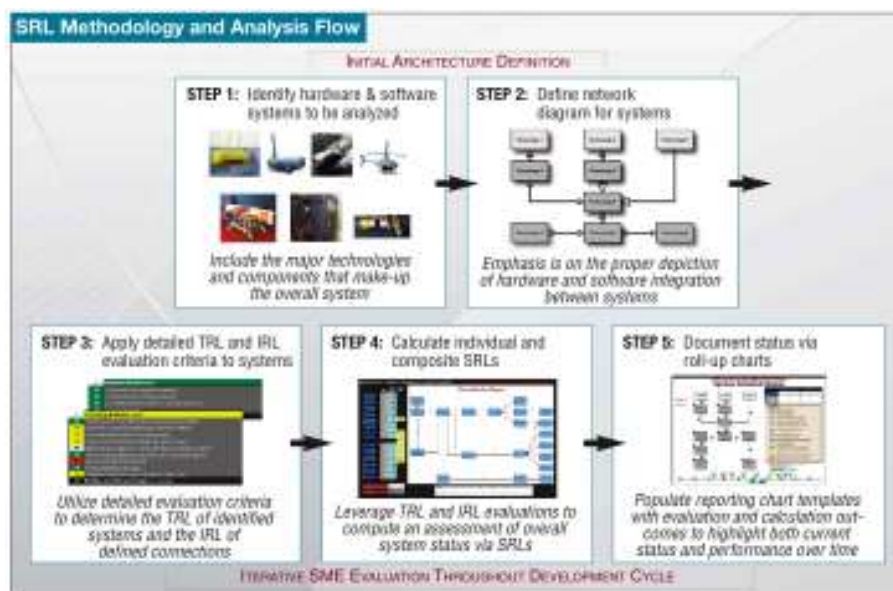

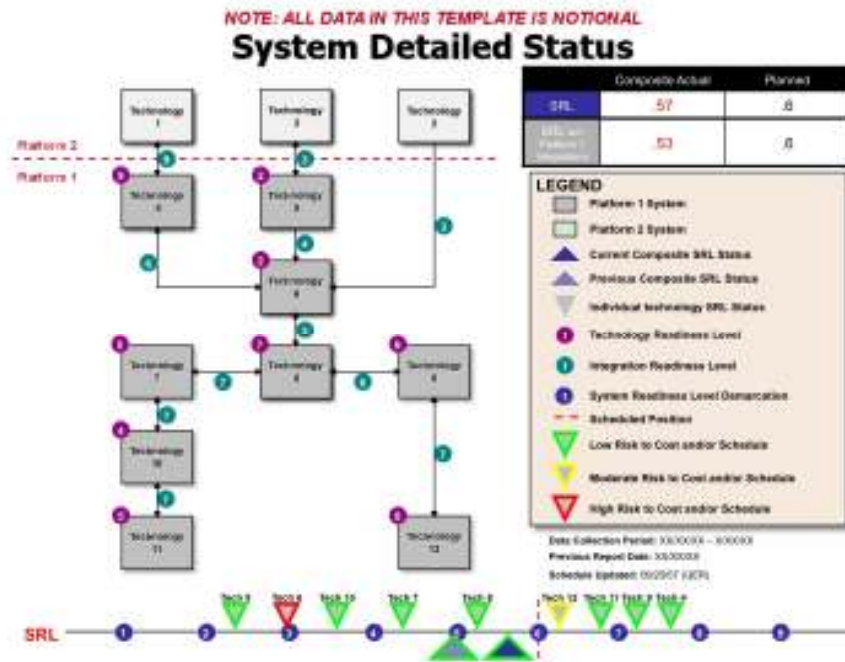**Figure 3. SRL Methodology and Analysis Flow**

Figure 4. Example of Documented Status via Roll-up Chart

In our development of an SRL scale, we strived to maintain a systems-focused approach that would create a metric(s) to address some of the current concerns with the TRL. What resulted was a set of metrics and an approach that can have the following implications on defense acquisition:

- The SRL, IRL, and TRL provide an enhanced capability alignment through the identification of specific technology, integration, and system maturities that can be used as a trade-study tool to select the most appropriate technologies and integrations to obtain the lowest amount of risk, cost, and time and satisfy a given customer need.

- The SRL [IRL, TRL] model can improve customer confidence in the acquisition manager by providing a qualification of system maturity in relation to system functionality. It can also provide improved understanding of the system's mission capabilities in terms of readiness criteria.

- The SRL can provide an assessment of maturity at multiple architectural layers. Any single SRL assessment contains multiple SRL assessments from the SRL vector, which can provide insight into the interdependencies of different sub-functions and how they fit within the larger architecture.

- The SRL can provide a fast, iterative assessment that can be repeated and traced during development. This can facilitate a valuable exercise in architecture examination and creation, which can allow for better system understanding and (re)formation.

- The SRL and IRL allow for other factors (in addition to technology readiness) as measures of maturity. In addition, decision-makers can consider factors such as obsolescing—by comparative analysis of multiple technologies to acquisition—and the optimization of technology maturation investment and transition funding. This is currently an area of future research.

- The SRL, IRL, and TRL provide common ontology to measure and describe acquisition development, system development and technology-insertion evaluation.

- The IRL reduces the uncertainty involved in integrating a technology into a system and identifies integration as a separate, specific metric.

Despite the utility of the SRL, it is not without a core limitation. That is, our tactical approach to the SRL was similar to that of calculating a student's grade point average (GPA)—in which ordinal data is given numeric value in order to assess overall progression or performance. This approach also incurs a key limitation to assessing a system's development. Accordingly, the SRL for one system cannot be compared to the SRL of another system unless they are the same system. For example, it is difficult to compare a student with a 3.2 GPA (on a 4.0 scale) in physics with a student that has a 3.8 GPA in biology. These students belong to different systems of education, but they are evaluated with the same system of metrics. Likewise, the SRL can be effective for assessing the progressive maturity of the system of interest, but it is questionable to compare the maturity progression of two systems against each other because of other inherent factors related to the context in which the system is being developed.

Further trials using real case studies are necessary in order to verify the formulation of the SRL, as well as to establish its validity. These will also be necessary in order to illustrate the benefits of SRL in terms of improved risk management and value added at key decision points along the acquisition lifecycle. When the validity of the SRL is established, it can then be expanded to incorporate, where necessary, other measures of readiness, such as Manufacturing Readiness Level (MRL). As with any research, the fundamental objective is to increase our understanding by asking questions that lead to more questions. Thus, for future research in system maturity assessment and defense acquisition, we propose some of the following questions:

- Are there variations in how system maturity assessment is used with various lifecycles, e.g., linear acquisition, evolutionary acquisition, revolutionary acquisition?

- What are the implications of system maturity levels for the integration of open systems into evolutionary acquisition?

- What are the impacts of disruptive technologies on systems maturity forecasting?

- How does vendor selection impact system maturity assessment?

- How do other maturity metrics, such as the Manufacturing Readiness Level (MRL), work with the IRL and SRL?

- How can the techniques of system maturity assessment be used for trade-off analysis of competing technologies or systems?

- What are the impacts of obsolescence to system maturity planning and road mapping?

- What are the single-technology refreshment optimization considerations for asynchronous refreshment frequency?

- What are the multi-objective optimization considerations for asynchronous refreshment frequency?

- What are the uncertainties surrounding the lifecycle curve for system maturity?

- How can we consider the environmental costs throughout a system's lifecycle?

6. Conclusions

We contend that the IRL is necessary because in some programs, integration elements have been overlooked and have resulted in major debacles. We also introduced the development of a system-focused approach for managing system development and for making effective and efficient decisions during the defense acquisition process. To accomplish this, we developed a SRL scale incorporating both the current TRL and the proposed IRL scale. We then described the foundations of the SRL and demonstrated the techniques for determining current readiness of a system to determine its position in the defense acquisition lifecycle. We summarized our approach (describing how it may be used within defense acquisition), showed a specific example of how the analysis could be reported, and provided some questions for future research.

The DoD Technology Readiness Assessment (TRA) states that "the TRA should not be the sole means of discovering technology risk" (DoD, 2005b). Furthermore, as stated earlier, the GAO has reported that the DoD needs additional metrics for evaluating weapons systems. While metrics can identify critical parameters, establish milestones to assess progress, provide direction for risk management/mitigation, or sustain entry and exit criteria for major milestones, we must keep in mind the four guidelines for effective and efficient metrics by Dowling and Pardoe (2005) as described earlier. Accordingly, we attempted to follow these guidelines and proposed the inclusion of a separate maturity scale to measure the progress of the development of the integration links of a system and the system as a whole.

We consider the TRL to be simple and understandable; however, some ambiguity exists, in part due to the extrapolation of the TRL beyond what it was intended to do. We believe that the IRL mimics the value of the TRL in that it is simple and understandable, but we contend that the interpretation of the individual IRL levels may need more clarification before the IRL can become a metric in practice. The combination of the TRL and IRL for the formulation of the SRL was not a simple endeavor, as many alternative mathematical approaches were pursued (Sauser et al., 2007). The chosen approach was used because it was the simplest and most robust with respects to its sensitivity to changes in any TRL or IRL within a system. While the addition

of any metric means incurring additional costs for an organization, we consider the addition of the IRL and SRL as a cost savings, as they are able to identify factors that have been significant failures in many system-development programs. Finally, we attempt to focus the development of these metrics based on data that would normally be available to any systems engineer (e.g., system architectures, baselines). Even with what we consider to be a valuable contribution to the assessment of system maturity, the additive value of "readiness" metrics carries with it the additive drawbacks: (a) Subjectivity and Human-intensiveness—human-intensive assessments can be overly optimistic and contain inherent variation or ambiguity that is averaged away and which some of the existing approaches may fail to prevent; and (b) Limited Focus—while this is not the intent, focusing on single or a limited subset of numbers can draw attention away from other core issues.

In conclusion, the conceptual development of these or any metrics and tools have outpaced their validation and verification in the field. What is necessary now is to have greater involvement from practitioners so the acquisition community can agree to a common measurement and language that can only improve the system development and acquisition process.

Acknowledgements

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