Defining an Integration Readiness Level for Defense Acquisition

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Abstract. There is a tremendous need to analyze system interoperability within Defense for both government and industry. Part of this challenge is the need for a metric that can be used as a common ontology and assess the state of interoperability in system's development and acquisition. Previous research developments have created an Integration Readiness Level (IRL) that complements the well-established Technology Readiness Level (TRL) of the Department of Defense. This paper expands upon this work with the objective of presenting a verified and validated IRL and supporting guide of critical maturation criteria. We will review the foundations of this IRL, describe our development of a "guide" to support the IRLs, present the results of a survey to assess the criticality of decision criteria in the "guide," and conclude with a discussion of the results and their implications to defense acquisition.

Introduction

Complex system development and integration has too often posed significant cost, schedule and technical performance risks to program managers, systems engineers, and development teams. Many risk factors have played a key role in degrading this process, but acceptable technology maturity has often been the principal driver, particularly in programs where innovation is fundamental to stakeholder requirements. This became an identified issue within the Department of Defense (DoD) in 1999 when the United States (U.S.) Government Accountability Office (GAO) stated that few metrics were used to gauge the impact of investments or the effectiveness of processes to develop, integrate, and transition technologies and that additional metrics were needed (GAO 1999). Furthermore, GAO would later state in a testimony before the U.S. Senate Subcommittee on Readiness and Management Support, Committee on Armed Services that the DoD needed to enable success through demonstrating value and credibility of new processes through the use of metrics (GAO 2002). In these reports GAO had recommended the implementation of Technology Readiness Levels (TRL), used by the National Aeronautics and Space Administration (NASA) since the 1980's, for assessing the maturity of advanced technologies so the associated risks could be effectively managed, controlled and mitigated, or retired. In an initial response to these inquiries, the DoD made constructive changes to its approach to acquisition: (1) assuring technologies are demonstrated to a high level of maturity before beginning a weapon system program and (2) using an evolutionary or phased approach to developing systems (GAO 2002), and began informally implementing TRL as a metric to assess the maturity of technologies before system development begins. In addition, they created DoD Instruction 5000.02 (DoD 2008) which establishes a requirement for Technology Readiness Assessments (TRAs), and a TRA Deskbook that provides an outline for performing a TRA (DoD 2005), which can include the use of TRL. The TRA Deskbook specifies that TRAs should be performed prior to each milestone review, but there is an inherent assumption in this guidance, and that is that the developmental items or Critical Technology Elements (CTE) are suitable for integration into the larger system. Given the complexity of integration, this may not be a valid assumption (Jain et al. 2008). The TRA Deskbook also states that "the TRA should not be the sole means of discovering technology risk" (DoD 2005), and as stated earlier, the GAO has reported that the DoD needs additional metrics for evaluating weapons systems development maturity.

With TRL's widespread use within NASA and the DoD, other government agencies and their contractors (e.g. Department of Energy (DoE), Sandia National Laboratory) have also adopted the TRL scale. Additionally, in the years following the introduction of TRL, a variety of other maturity metrics have been proposed as decision support tools for acquisitions (e.g. Design Readiness Level, Manufacturing Readiness Level; Software Readiness Level; Operational Readiness Level; Human Readiness Levels; Habitation Readiness Level; Capability Readiness Levels (Bilbro 2007; Connelly et al. 2006; Cundiff 2003)). However, as TRL has matured and complementary or alternative maturity metrics have been created each has faltered in addressing technology integration, the major shortcoming with TRL as identified in the literature (Cundiff 2003; Dowling and Pardoe 2005; Mankins 2002; Meystel et al. 2003; Moorehouse 2001; Shishko, Ebbeler, and Fox 2003; Smith 2005; Valerdi and Kohl 2004).

The metrics and ontology for the coupling and maturation of multiple technologies and systems has been shown to be an unresolved issue of strategic relevance (Watts and Porter 2003; Nambisan 2002). Additionally, component level considerations relating to integration, interoperability, and sustainment become equally or more important from a systems perspective during acquisition (Sandborn et al. 2003). Indeed, Mosher (2000) described system integration as the most difficult part of an acquisition program. Unfortunately, even with the implementation of new processes and practices within DoD acquisition, the challenges are still significant. To compound this, DoD plans to invest an estimated $900 billion to develop and procure weapons systems at a pace that far exceeds the availability of resources over the next five years (GAO 2008).

While technology and system development theoretically follow similar maturation paths, ultimately a technology is inserted into a system (e.g. evolutionary acquisition) based on its maturity, functionality, and environmental readiness as well as its ability to interoperate with the intended system. However, many of the practices that bring about successful implementation of a technology or system into its operational environment are not always effectively practiced during development (Parsons 2006). Fundamentally, any system under development is composed of core technology components and their linkages (i.e. architecture). Henderson and Clark (1990) emphasize that systems often fail because attention is given to the technology and knowledge of the linkages/integrations is overlooked. This has an impact on the systems' technical evolution, organizational experience, recurrent task, and technical knowledge as they relate to the component linkages in addition to the product architecture, communication channels, and problem solving strategies.

While TRL provides the metric for describing component knowledge, based on Henderson and Clark (1990), one would still be interested in a metric that provides a description of integration. While there have been some efforts to develop metrics that can be used to evaluate integration maturity [e.g. (DoD 1998, March 30), (Mankins 2002), (Fang, Hu, and Han 2004), (Nilsson, Nordhagen, and Oftedal 1990)], the need is for a metric that can be understood by all the relevant stakeholders, evaluates integration maturity, and can be used with TRL to potentially determine a system maturity.

In response to this, Gove et al. (Gove 2007; Gove, Sauser, and Ramirez-Marquez 2007) created an Integration Readiness Level (IRL) to measure integration maturity on a scale similar to TRL with the objective that it could be used in conjunction with TRL and a TRA to provide a system-level readiness assessment (Sauser, Ramirez-Marquez, Henry et al. 2008; Sauser et al. 2006; Sauser, Ramirez-Marquez, Magnaye et al. 2008). While these IRLs have been defined and tested (Gove 2007; Gove, Sauser, and Ramirez-Marquez 2007; Sauser, Ramirez-Marquez, Henry et al. 2008; Sauser, Ramirez-Marquez, Magnaye et al. 2008), there is a significant need to develop a formal, structured set of decision criteria or a "guide" to help practitioners determine appropriate IRLs as part of a TRA or even system maturity assessment. Thus, this paper expands upon this previous work with the objective of presenting a verified and validated IRL and supporting "guide." In this paper we will review the foundations of the IRL illustrated by Gove, et al., describe our development of a "guide" for these IRLs, present the results of a survey to assess the criticality of decision criteria in the "guide," and conclude with a discussion of the results and their implications to defense acquisition.

Foundations for an Integration Readiness Level

The application of ontology metrics to support integration has been extensively used in the computer industry to define coupling of components (Orme, Yao, and Etzkorn 2006, 2007), but a common ontological approach to technology integration for system development has been far less developed. The first attempt to address this was done 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 index and choosing between competing alternative technologies, but 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, et. al. (Gove 2007; Gove, Sauser, and Ramirez-Marquez 2007) performed a review of aerospace- and defense-related literature to identify the requirements for developing a seven-level integration metric which they called Integration Readiness Level (IRL). These factors led to the definition of requirements for an integration metric. These requirements included:

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

Using these requirements Gove, et al. assessed Mankin's Integrated Technology Index (Mankins 2002) , Nilsson, et al.'s integration metric (Nilsson, Nordhagen, and Oftedal 1990), Fang, et al.'s Interoperability Assessment Model (Fang, Hu, and Han 2004) and their 7-level IRL. While none of these methods met all the stated requirements, the analysis resulted in a modified 9-level IRL that did. The resultant 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 are described in Table 1.

Table 1: Integration Readiness Levels (Gove 2007; Gove, Sauser, and Ramirez-Marquez 2007)

	IRL	DEFINITION	DESCRIPTION
PRAGMATIC	**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/defect that could not be discovered until the interaction of the two integrating technologies was observed in the system environment.
SYNTACTIC	**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 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.
SEMANTIC	**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 **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 detail to allow characterization of the relationship.	This is the lowest level of integration readiness and describes the selection of a medium for integration.

For further clarification, the nine levels of IRL presented in Table 1 can be understood as having three stages of integration definition: semantic, syntactic, and pragmatic. Semantics is about relating meaning with respects to clarity and differentiation. Thus IRL 1-3 are considered fundamental to describing what we define as the three principles of integration: interface, interaction, and compatibility. We contend that these three principles are what define the subsistence of an integration effort. The next stage is Syntactic, which is defined as a conformance to rules. Thus IRLs 4-7 are about assurance that an integration effort is in compliance with specifications. The final stage is Pragmatic, which relates to practical considerations. Thus, IRLs 8-9 are about the assertion of the application of an integration effort.

Gove, et al. also evaluated these integration maturity metrics with multiple system case studies, e.g. Mars Climate Orbiter, Ariane 5, two Hubble Space Telescope systems, 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.

Guide (and Survey) Development and Results

As previously stated, one of the principal goals of this paper was to begin the development of a verified and validated set of IRL metrics that could be useful in developing a more comprehensive TRA methodology that addresses the complexity of integration in a less heuristic or subjective manner. In the context of this effort, verification addresses whether or not the correct IRLs were identified/defined and validation addresses the relevance or criticality of each IRL. Thus, in creation of the IRL guide, we used two forms of assessment to specify the decision criteria that may define each IRL: (1) review of systems engineering and acquisition standards, policy, research, and other guidance documents (e.g. DoD 5000.02, INCOSE Systems Engineering Handbook, IEEE 15288), and (2) discussions with subject matter experts (SME) in systems engineering, program management, and acquisition across government, industry, and academia. In all cases an effort was made to capture those documents (e.g., Systems Engineering Plan, TEMP) or document content (e.g., requirements, architecture, compatibility, interoperability, etc.) deemed most significant to an assessment of integration maturity. What resulted was a list of decision criteria for each IRL as shown in Tables 2-10. It should be emphasized that the list of maturity metrics under each IRL is not in order of criticality. It should also be emphasized that the lists are not considered to be comprehensive or complete; they are merely an attempt to capture some of the more important decision criteria associated with integration maturity in order to afford practitioners the opportunity to assess the criticality of each decision criteria relative to the IRL it is listed under.

Thus, to establish further verification and validation to the decision criteria, we deployed a survey that asked SMEs to evaluate each decision criteria in the context of its criticality to the specified IRL. The criticality criteria for assessing the IRL decision criteria were defined as:

- Critical – IRL cannot be assessed without it
- Essential – without it, IRL can be assessed but with low to medium confidence in the results
- Enhancing – without it, IRL can be assessed with medium to high confidence in the results
- Desirable – without it, IRL can be assessed with very high confidence in the results
- N/A – the metric is not applicable to the IRL assessment

We sampled 33 SMEs from government and industry with experience in systems engineering, software engineering, program management, and/or acquisition. Table 2 indicates the demographics of the 33 SMEs with respects to years of experience and employment in government or industry. Of these, 85% had greater than five years experience and 33% had greater than 20 years of experience.

Table 2: Demographics of Subject Matter Experts

Sector	Sample	Years of Experience				
		0-5	5-10	10-15	15-20	20+
Government	13	2	2	1	1	7
Industry	20	3	9	2	2	4
TOTAL	33	5	11	3	3	11

For each decision criteria we calculated the relative and cumulative frequencies of the criticalities (reported in Tables 2-10). Relative frequency is the proportion of all responses in the data set that fall in the category (i.e. decision criteria for any IRL). Cumulative relative frequency allows for additional information to be understood about the sensitivity of the response frequency based on a class interval (i.e. Critical/Essential versus Enhancing/Desirable). This is meant to help to identify whether the criticality categories originally identified are too fine and should be modified.

Semantic (IRL 1-3)

This is the stage at which we fundamentally define the integration needs and the manner in which it will take place. From Tables 2-4 we observe that in IRLs 1-3 a single decision criterion for each IRL is rated as critical by the respondents. For IRL 1 this is *1.1 Principal integration technologies have been identified*. This can indicate that at this level of maturity the criticality of the integration is in the proper identification of the technologies to be integrated.

Obviously, identifying integration elements is the first step in successful integration. Though it may seem trivial, this activity is indispensable as since unknown or undefined elements can derail a project that is well along in the development process. Application of proper time and resources at this stage is essential in order to build a proper foundation for future planning and maturation activities. For IRL 2, we observe that the criticality has transferred to an understanding of the input/output (I/O) for the integration.

With the elements of the system integration effort defined at IRL 1 the next step logically moves on to the definition of the I/O requirements of the system. This was identified by SMEs as a critical step and is needed in order to understand the type and complexity of the integrations between technology elements. Indeed, all integration is not the same and survey results show that successful system integration is highly dependent on the accurate understanding of the degree of work needed to successfully connect disparate systems. This information then drives factors such as the application of cost, schedule, and resources during later development activities.

At IRL 3, the data denotes an importance in the diagramming of the system interfaces. To reach this stage of maturity requires leveraging all of the information defined previously. The identified technologies can be mapped and the I/O requirements are drivers for how those elements are to be connected. At this stage the system truly begins to take shape as an interconnected system and the functionality of the parts can be seen from a system perspective. In many cases, development projects tend to bypass or minimize this stage because of time or funding constraints. However, the lack of upfront planning comes back in the form of reduced or unintended functionality later in development that can lead to even larger time and resource hits. Only by completing a comprehensive mapping of the system early in development can the true magnitude of the task be understood and successfully planned for.

In looking back at the key identified elements of the semantic stage we see a clear flow mapped out by integration SMEs. By considering the fundamental components of an integration effort as the technologies, their identified linkage (e.g. I/O), and a representation of this relationship (e.g. architecture), then our data indicates this in *1.1 Principal integration technologies have been identified*, *2.2 Inputs/outputs for principal integration technologies are known, characterized and documented*, and *3.4 High-level system interface diagrams have been completed*. This progression is in keeping with the best practices laid out by numerous studies and system engineering guides and reflects a steady evolution of knowledge from the time that the components required are identified until a formal architecture is developed.

Syntactic (IRL 4-7)

For IRLs 4 and 5, we see less clarity in the identification of IRL decision criteria with more ambiguity in what is most important. This is not too different from what has been described with TRL, in that the transition from TRL 3 to 4 is the most ill defined and difficult to determine (Austin et al. 2008). A great deal of this uncertainty can be attributed to the broad array of activities taking place at this stage of development, many of which are highly dependent on the type of project being worked. Depending on the complexity, goals, and knowledge base of work being undertaken, key activities could vary dramatically. For an effort that is truly revolutionary and untested, significantly more attention would be spent on risk analysis, quality assurance, and modeling and simulation whereas projects involving work of a more known quantity would be justified in focusing less in this areas and instead leveraging the significant number of lessons learned from projects that have gone before them. As reflected by the tightly grouped results, all criteria are important considerations and should receive attention while those that are of greatest impact to the project should be identified via careful consideration of project needs, priorities and risks.

For IRL 6 and 7 we begin to see more clarity again as IRL 6 shows two decision criteria as being critical. This is reflective of the common string of development activities that being to again reign supreme independent of the type of project being worked. As the technology elements are brought together and the interfaces are fully defined and made to function an urgent need to initiate testing comes about for development efforts. In order to mitigate the difficulty of large system testing later in the development cycle it is viewed as a critical step that smaller elements or modules of functionality be flexed in order to assess the completeness of their integration. (see *6.3 Individual modules tested to verify that the module components (functions) work together*). This then evolves as these modules are further integrated into an overarching functional system for continued testing. For IRL 7 we indicate that end-to-end testing (see *7.1 End-to-end Functionality of Systems Integration has been successfully demonstrated*) is critical before moving to our next phase – Pragmatic (or operation). We believe this is consistent with prescribed system development phases (DoD 2008). Unfortunately, many programs see this critical end-to-end testing phase squeezed in a race to field a capability or stay on schedule. In order to successfully pass the IRL 7 stage, however, it is essential that a complete and thorough test of the newly developed system be conducted to prove that the functionality is as desired and that the reliability of the system is suitable for operation.

Pragmatic (IRL 8-9)

Since Pragmatic addresses the operational context of the integration, it is not surprising that decision criteria such as meeting requirements become paramount. At this phase of system maturation, developmental and operational testing activities are used to determine the degree to which the system meets the requirements outlined for the effort at project initiation (*8.1 All integrated systems able to meet overall system requirements in an operational environment; 8.2 System interfaces qualified and functioning correctly in an* *operational environment*).

These activities ensure that the system can function fully not only in a laboratory or experimental situation but in a realistic environment where many factors cannot be readily controlled or anticipated. Unfortunately, in recent years there has been a trend towards the waiving of requirements not attained by this system late in the design cycle. Instead of ensuring the that system is fully capable, the symptoms of a dysfunctional integration process often result in the acceptance of a system that is of a lesser capability than was desired or needed. This is one of the shortcomings that the development of a rigorous integration scale is intended to mitigate. The final stage of integration maturity, IRL 9, can only be attained after a system has truly been flexed by the operator and is impendent of the type of project undertaken. The important criteria principally take into account quantification and demonstration in operational environment (*9.1 Fully integrated system has demonstrated operational effectiveness and suitability in its intended or a representative operational environment*), and failure rate characterization (*9.2 Interface failures/failure rates have been fully characterized and are consistent with user requirements*) all of which were rated high by SMEs. At this final stage the fruits of a successful system maturation process can be seen through a highly functional capability with robust reliability. An inability to achieve satisfactory results should be prevented through the proper application and tracking of Technology and Integration Readiness Levels.

Table 2: IRL 1 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 1 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
1.1 Principal integration technologies have been identified	0.58	0.33	0.03	0.06	0.00	0.91	0.09
1.2 Top-level functional architecture and interface points have been defined	0.39	0.52	0.06	0.03	0.00	0.91	0.09
1.3 Availability of principal integration technologies is known and documented	0.15	0.39	0.36	0.06	0.03	0.55	0.42
1.4 Integration concept/plan has been defined/drafted	0.18	0.45	0.21	0.12	0.03	0.64	0.33
1.5 Integration test concept/plan has been defined/drafted	0.12	0.36	0.33	0.18	0.00	0.48	0.52
1.6 High-level Concept of Operations and principal use cases have been defined/drafted	0.06	0.21	0.55	0.15	0.03	0.27	0.70
1.7 Integration sequence approach/schedule has been defined/drafted	0.06	0.36	0.33	0.21	0.03	0.42	0.55
1.8 Interface control plan has been defined/drafted	0.03	0.12	0.67	0.18	0.00	0.15	0.85
1.9 Principal integration and test resource requirements (facilities, hardware, software, surrogates, etc.) have been defined/identified	0.09	0.36	0.30	0.18	0.06	0.45	0.48
1.10 Integration & Test Team roles and responsibilities have been defined	0.12	0.24	0.33	0.24	0.06	0.36	0.58

Table 3: IRL 2 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 2 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
2.1 Principal integration technologies function as stand-alone units	0.18	0.27	0.24	0.30	0.00	0.45	0.55
2.2 Inputs/outputs for principal integration technologies are known, characterized and documented	0.52	0.36	0.06	0.06	0.00	0.88	0.12
2.3 Principal interface requirements for integration technologies have been defined/drafted	0.39	0.33	0.24	0.03	0.00	0.73	0.27
2.4 Principal interface requirements specifications for integration technologies have been defined/drafted	0.27	0.45	0.24	0.03	0.00	0.73	0.27
2.5 Principal interface risks for integration technologies have been defined/drafted	0.06	0.24	0.61	0.09	0.00	0.30	0.70
2.6 Integration concept/plan has been updated	0.06	0.42	0.42	0.09	0.00	0.48	0.52
2.7 Integration test concept/plan has been updated	0.09	0.27	0.52	0.12	0.00	0.36	0.64
2.8 High-level Concept of Operations and principal use cases have been updated	0.12	0.18	0.45	0.21	0.03	0.30	0.67
2.9 Integration sequence approach/schedule has been updated	0.09	0.27	0.45	0.18	0.00	0.36	0.64
2.10 Interface control plan has been updated	0.06	0.30	0.61	0.03	0.00	0.36	0.64
2.11 Integration and test resource requirements (facilities, hardware, software, surrogates, etc.) have been updated	0.15	0.39	0.27	0.15	0.03	0.55	0.42
2.12 Long lead planning/coordination of integration and test resources have been initiated	0.12	0.30	0.30	0.24	0.03	0.42	0.55
2.13 Integration & Test Team roles and responsibilities have been updated	0.03	0.15	0.58	0.21	0.03	0.18	0.79
2.14 Formal integration studies have been initiated	0.12	0.33	0.21	0.21	0.12	0.45	0.42

Table 4: IRL 3 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 3 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
3.1 Preliminary Modeling & Simulation and/or analytical studies have been conducted to identify risks & assess compatibility of integration technologies	0.18	0.36	0.45	0.00	0.00	0.55	0.45
3.2 Compatibility risks and associated mitigation strategies for integration technologies have been defined (initial draft)	0.09	0.39	0.52	0.00	0.00	0.48	0.52
3.3 Integration test requirements have been defined (initial draft)	0.15	0.48	0.24	0.12	0.00	0.64	0.36
3.4 High-level system interface diagrams have been completed	0.48	0.27	0.24	0.00	0.00	0.76	0.24
3.5 Interface requirements are defined at the concept level	0.24	0.70	0.06	0.00	0.00	0.94	0.06
3.6 Inventory of external interfaces is completed	0.24	0.33	0.42	0.00	0.00	0.58	0.42
3.7 Data engineering units are identified and documented	0.06	0.45	0.24	0.21	0.03	0.52	0.45
3.8 Integration concept and other planning documents have been modified/updated based on preliminary analyses	0.18	0.27	0.42	0.09	0.03	0.45	0.52

Table 5: IRL 4 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 4 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
4.1 Quality Assurance plan has been completed and implemented	0.18	0.27	0.36	0.15	0.03	0.45	0.52
4.2 Cross technology risks have been fully identified/characterized	0.12	0.52	0.33	0.03	0.00	0.64	0.36
4.3 Modeling & Simulation has been used to simulate some interfaces between components	0.06	0.24	0.70	0.00	0.00	0.30	0.70
4.4 Formal system architecture development is beginning to mature	0.09	0.52	0.36	0.03	0.00	0.61	0.39
4.5 Overall system requirements for end users' application are known/baselined	0.24	0.55	0.15	0.06	0.00	0.79	0.21
4.6 Systems Integration Laboratory/Software test-bed tests using available integration technologies have been completed with favorable outcomes	0.09	0.52	0.36	0.03	0.00	0.61	0.39
4.7 Low fidelity technology "system" integration and engineering has been completed and tested in a lab environment	0.06	0.36	0.52	0.06	0.00	0.42	0.58
4.8 Concept of Operations, use cases and Integration requirements are completely defined	0.12	0.30	0.55	0.00	0.03	0.42	0.55
4.9 Analysis of internal interface requirements is completed	0.09	0.61	0.27	0.03	0.00	0.70	0.30
4.10 Data transport method(s) and specifications have been defined	0.12	0.36	0.48	0.03	0.00	0.48	0.52
4.11 A rigorous requirements inspection process has been implemented	0.27	0.30	0.21	0.21	0.00	0.58	0.42

Table 6: IRL 5 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 5 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
5.1 An Interface Control Plan has been implemented (i.e., Interface Control Document created, Interface Control Working Group formed, etc.)	0.33	0.58	0.06	0.00	0.03	0.91	0.06
5.2 Integration risk assessments are ongoing	0.06	0.48	0.45	0.00	0.00	0.55	0.45
5.3 Integration risk mitigation strategies are being implemented & risks retired	0.03	0.52	0.39	0.06	0.00	0.55	0.45
5.4 System interface requirements specification has been drafted	0.39	0.36	0.24	0.00	0.00	0.76	0.24
5.5 External interfaces are well defined (e.g., source, data formats, structure, content, method of support, etc.)	0.27	0.55	0.18	0.00	0.00	0.82	0.18
5.6 Functionality of integrated configuration items (modules/functions/assemblies) has been successfully demonstrated in a laboratory/synthetic environment	0.21	0.52	0.27	0.00	0.00	0.73	0.27
5.7 The Systems Engineering Management Plan addresses integration and the associated interfaces	0.15	0.18	0.33	0.12	0.21	0.33	0.45
5.8 Integration test metrics for end-to-end testing have been defined	0.12	0.33	0.52	0.03	0.00	0.45	0.55
5.9 Integration technology data has been successfully modeled and simulation	0.06	0.67	0.18	0.09	0.00	0.73	0.27

Table 7: IRL 6 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 6 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
6.1 Cross technology issue measurement and performance characteristic validations completed	0.27	0.39	0.33	0.00	0.00	0.67	0.33
6.2 Software components (operating system, middleware, applications) loaded onto subassemblies	0.45	0.33	0.12	0.03	0.06	0.79	0.15
6.3 Individual modules tested to verify that the module components (functions) work together	0.48	0.42	0.09	0.00	0.00	0.91	0.09
6.4 Interface control process and document have stabilized	0.09	0.48	0.36	0.03	0.03	0.58	0.39
6.5 Integrated system demonstrations have been successfully completed	0.21	0.58	0.15	0.06	0.00	0.79	0.21
6.6 Logistics systems are in place to support Integration	0.12	0.42	0.27	0.18	0.00	0.55	0.45
6.7 Test environment readiness assessment completed successfully	0.06	0.52	0.33	0.06	0.03	0.58	0.39
6.8 Data transmission tests completed successfully	0.18	0.64	0.06	0.06	0.06	0.82	0.12

Table 8: IRL 7 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 7 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
7.1 End-to-end Functionality of Systems Integration has been successfully demonstrated	0.61	0.18	0.21	0.00	0.00	0.79	0.21
7.2 Each system/software interface tested individually under stressed and anomalous conditions	0.33	0.55	0.12	0.00	0.00	0.88	0.12
7.3 Fully integrated prototype demonstrated in actual or simulated operational environment	0.42	0.45	0.09	0.03	0.00	0.88	0.12
7.4 Information control data content verified in system	0.24	0.55	0.18	0.00	0.03	0.79	0.18
7.5 Interface, Data, and Functional Verification	0.33	0.55	0.09	0.03	0.00	0.88	0.12
7.6 Corrective actions planned and implemented	0.15	0.48	0.27	0.09	0.00	0.64	0.36

Table 9: IRL 8 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 8 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
8.1 All integrated systems able to meet overall system requirements in an operational environment	0.85	0.12	0.03	0.00	0.00	0.97	0.03
8.2 System interfaces qualified and functioning correctly in an operational environment	0.61	0.36	0.03	0.00	0.00	0.97	0.03
8.3 Integration testing closed out with test results, anomalies, deficiencies, and corrective actions documented	0.39	0.52	0.09	0.00	0.00	0.91	0.09
8.4 Components are form, fit, and function compatible with operational system	0.42	0.48	0.06	0.03	0.00	0.91	0.09
8.5 System is form, fit, and function design for intended application and operational environment	0.42	0.45	0.09	0.03	0.00	0.88	0.12
8.6 Interface control process has been completed/closed-out	0.24	0.45	0.24	0.06	0.00	0.70	0.30
8.7 Final architecture diagrams have been submitted	0.36	0.12	0.42	0.09	0.00	0.48	0.52
8.8 Effectiveness of corrective actions taken to close-out principal design requirments has been demonstrated	0.24	0.48	0.24	0.03	0.00	0.73	0.27
8.9 Data transmission errors are known, characterized and recorded	0.36	0.33	0.21	0.09	0.00	0.70	0.30
8.10 Data links are being effectively managed and process improvements have been initiated	0.18	0.52	0.27	0.03	0.00	0.70	0.30

Table 10: IRL 9 Decision Criteria and Criticality Assessment

	Relative Frequency (RF); n = 33					Cumulative RF	
IRL 9 Decision Criteria	Critical	Essential	Enhancing	Desirable	N/A	Critical Essential	Enhancing Desirable
9.1 Fully integrated system has demonstrated operational effectiveness and suitability in its intended or a representative operational environment	0.82	0.09	0.09	0.00	0.00	0.91	0.09
9.2 Interface failures/failure rates have been fully characterized and are consistent with user requirements	0.64	0.27	0.06	0.03	0.00	0.91	0.09
9.3 Lifecycle costs are consistent with user requirements and lifecycle cost improvement initiatives have been initiated	0.24	0.42	0.21	0.09	0.03	0.67	0.30

Summary, Validity, and Future Research

Theoretically the two activities of technology development and integration could be represented on a linear plane as shown in Figure 1. Although we do not contend that these developments are parallel paths, thus the purpose of the dashed line is to indicate that there is a dynamic, non-linear causality akin to the embedded systems engineering life cycle (or “V within the V within the V…”).

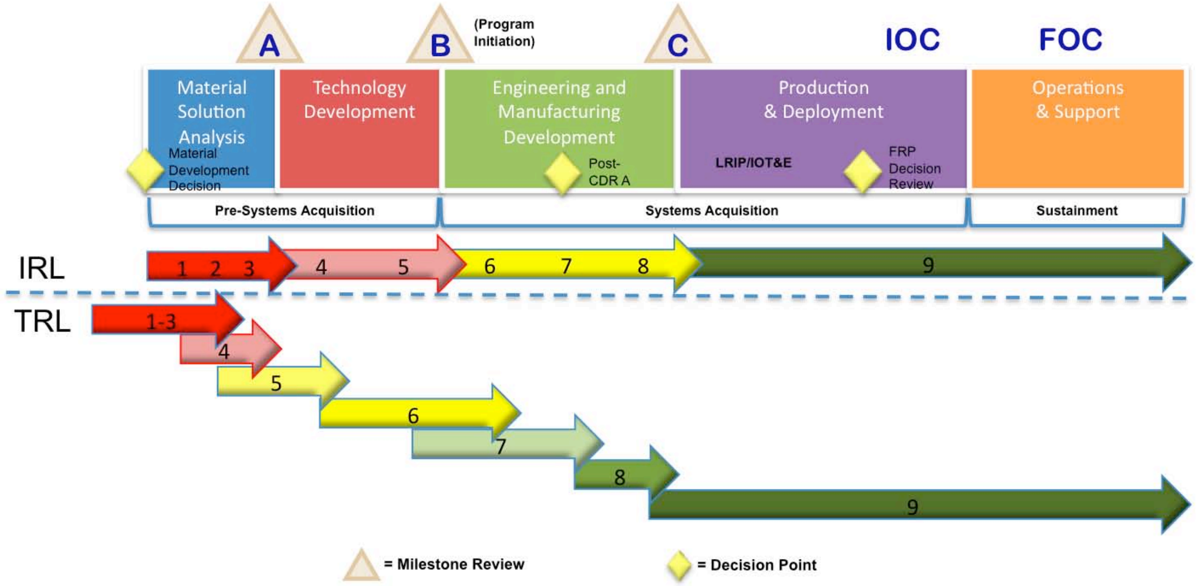

Figure 1: TRL/IRL with Defense Acquisition Lifecycle (DoD 2008)

For this study the participants were asked to assess the criticality of each IRL metric within the context of the IRL they were listed under rather than being allowed to identify metrics that they considered useful in assessing the IRL as defined. In other words, participants were given a “canned” list of metrics and a “fixed” context (i.e., the IRL construct and the specific IRL that a set of metrics was assigned to). Therefore, it is recommended that additional work be conducted (perhaps via multiple working groups comprised of seasoned practitioners or SMEs) to review and modify the current list of IRL metrics while using the criticality assessment as a baseline. This effort should address two aspects of the IRL guide: the metrics themselves and the weight that should be assigned to each based on criticality data. Additionally, the issue of whether or not the integration type is an important factor concerning how an IRL is determined needs to be examined.

Finally, integration is a complex topic and the respondents may have been biased by the type of integration experience they have had (i.e., software, hardware, software and hardware, etc.); the wording of each IRL metric may have been interpreted differently by the participants; and some decision criteria may belong within a different IRL scale, thereby altering its criticality.

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