# A Comprehensive Review and Analysis of Maturity Assessment Approaches for Improved Decision Support to Achieve Efficient Defense Acquisition

Nazanin Azizian, Dr. Shahram Sarkani, Dr. Thomas Mazzuchi

*Abstract*— **Based on multiple reviews of major defense acquisition programs, the Government Accountability Office (GAO) has consistently reported that the Department of Defense (DoD) acquisition programs are experiencing difficulties in terms of schedule slips, cancellations, and failure to meet performance objectives due to insufficiently mature technology, unstable design, and a lack of manufacturing maturity. The GAO claimed that "maturing new technology before it is included in a product is perhaps the most determinant of the success of the eventual product or weapon system." As a result, the DoD adopted the Technology Readiness Level (TRL) metric as a systematic method to assess technology maturity. However, as a result of increasing complexity of defense systems and the lack of objectivity of the tool, the TRL metric is deficient in comprehensively providing insight into the maturity of technology. Objective and robust methods that can assess technology maturity accurately and provide insight into risks that lead to cost overruns, schedule delays, and performance degradation are imperative for making well-informed procurement decisions.**

**Realizing this challenge, numerous other models and methods have been developed to efficiently supplement and augment the TRL scale, as well as provide new means of evaluating technology maturity and readiness. The work presented in this paper has investigated the literature, and leading research and industrial practices for technology maturity assessment techniques, which are then analyzed using the SWOT (Strength, Weakness, Opportunity, Strength) model. The right maturity assessment techniques at the right time can enable government agencies and contractors to produce products that are cheaper, better, and made faster by closing knowledge gaps at critical decision points. This paper provides a comprehensive review and analysis of the prominent maturity assessment techniques in order to provide a selection criterion for decision makers to choose the best fit method for their program.**

*Index Terms*—**Technology Maturity, Technology Readiness, TRL.**

## I. Introduction

Successful parallel development and integration of complex systems result in successful programs. Complex systems are comprised of multiple technologies and their integrations. Due to scale and complexity of systems, stakeholders want confidence that risk is minimal and the probability of successful technology development and integration is high before investing large sums of money. Confidence is achieved when it is ensured that the developed or improved technologies can meet system requirements. As a result, quantitative assessment tools that can provide insight

on whether a group of separate technologies at various maturity levels can be integrated into a complex system at a low risk is beneficial to the success of a program and can help support decision making of stakeholders.

Tetlay and John [1] call the 21st century "The Systems Century" due the increasing complexity and high-integration of technological products. They contend that assessing system maturity and readiness during the life-cycle of development is imperative to the overall success of the system. Tetlay and John [1] argue that in recent years high interest is taken in metrics such as the Technology Readiness Level (TRL), System Readiness Level (SRL), Manufacturing Readiness Level (MRL), Integration Readiness Level (IRL) and other metrics as avenues to measure maturity and readiness of systems and technologies. These metrics are used to assess the risk associated with the development and operation of technologies and systems; therefore they are a way of ensuring that unexpected will not occur.

However, literature has revealed gaps in clearly specifying whether the objective of the metrics and methods is to measure maturity or readiness. In general, maturity and readiness are used interchangeably. In addition, in most cases the applicability of tools and methods toward technology versus a system is vague. Literature does not distinguish between maturity and readiness, and rarely specifies whether a method has been designed for a system or a technology.

This research will generalize maturity and readiness as one entity and refer to them throughout this paper interchangeably. The objective of this research is to develop a comprehensive assessment review of methods and tools used to evaluate the maturity and readiness of technology and systems. Although a technology and a system are not the same, many of the methods described in this paper do not distinguish between them.

Systematically measuring technology and system maturity is a multi-dimensional process that cannot be performed comprehensively by a one-dimensional metric. Although the TRL metric has been endorsed by the government and many industries, it captures only a small part of the information that stakeholders need to support their decisions. This paper presents other maturity assessment methods that have been developed other rectify this shortcomings of the TRL.

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## II. Background

### A. Problem Statement

Literature repeatedly denotes that acquisition programs experience cost overruns, schedule slips, and performance problems [2-14]. Based on a review of major defense acquisition programs, the Government Accountability Office (GAO) has consistently reported that the Department of Defense (DoD) acquisition programs are experiencing difficulties in terms of schedule slips, cancellations, and failure to meet performance objectives as a result of insufficiently mature technology, unstable design, and a lack of manufacturing maturity. The GAO claimed that "maturing new technology before it is included in a product is perhaps the most determinant of the success of the eventual product or weapon system" [8]. More recently, based on assessment of 72 Weapons Programs, the GAO reported in March 2008 [7] that

> *"none of them had proceeded through system development meeting the best practices standards for mature technologies, stable design, or mature production processes by critical junctures of the program, each of which are essential for achieving planned cost, schedule, and performance outcomes"*

Further, the GAO [7] reported that in the fiscal year 2007, the total acquisition cost of major defense programs have risen 26% from the initial estimate, while development costs grew by 40%, and programs have failed to deliver the promised capabilities. The trends in cost and schedule growth in these defense programs over the years are depicted in figure 1.

| Analysis of DOD Major Defense Acquisition Program Fiscal year 2008 | | | |
|---|---|---|---|
| | Fiscal Year | | |
| | 2000 Portfolio | 2005 Portfolio | 2007 Portfolio |
| Number of Programs | 75 | 91 | 95 |
| Total Planned Commitments | $790 Billion | $1.5 Trillion | $1.6 Trillion |
| Commitments Outstanding | $380 Billion | $887 Billion | $858 Billion |
| | Portfolio Performance | | |
| Change to total RDT&E costs from first estimate | 27% | 33% | 40% |
| Change in total acquisition cost from first estimate | 6% | 18% | 26% |
| Estimated total acquisition cost growth | $42 Billion | $202 Billion | $295 Billion |
| Share of programs with 25 percent or more increase in program acquisition unit cost | 37% | 44% | 44% |
| Average schedule delay in delivering initial capabilities | 16 Months | 17 Months | 21 Months |

**Figure 1: GAO Assessments of Major Defense Acquisition Programs**

Over the past 6 years the GAO has been reporting to the DoD that its weapons system acquisition programs are suffering in the area of cost growth and schedule delays, and unfortunately in a 2008 report the GAO continued to state that these cost and schedule problems have not been rectified. The resulting cost overrun and schedule delays is of no surprise because no program followed the best practices standards for maturing technology, stabilizing design, and maturing production process. In fact the GAO (2008) reported that 88% of the assessed programs began system development without fully maturing critical technologies; 96% of the programs had not demonstrated the stability of their designs before entering system demonstration phase; and no program had fully matured their production processes before entering production [7]. All in all, the GAO concluded that DoD programs enter various phases of acquisition and product development knowledge gaps that result in design, technology, and production risks.

### B. DoD Acquisition Lifecycle Famework

The DoD has adopted Evolutionary acquisition as an strategy to deliver an operational capability over several increments, where each increment is dependent on a sufficiently defined technology maturity level. The objective of evolutionary acquisition is to quickly hand off a capability to a user in a manner in which the technology development phase successively continues until the required technology maturity is achieved and prototypes of system components are produced. Each increment is comprised of a set of objectives, entrance, and exit criteria [15]. The stages of the DoD acquisition life-cycle are depicted in figure 2.

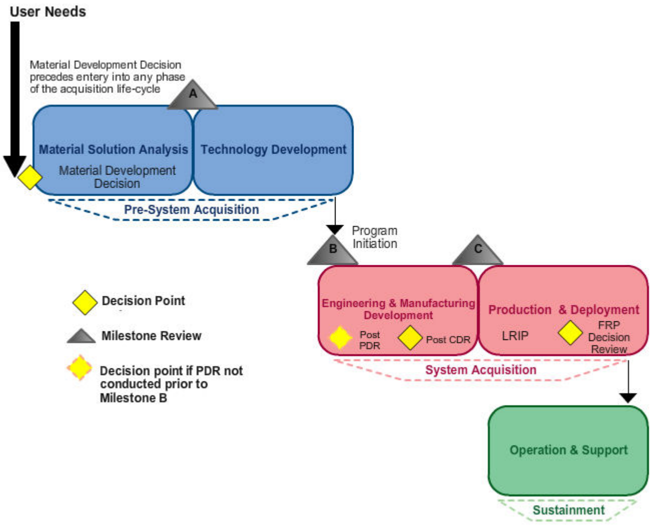


**Figure 2: DoD Acquisition Life-Cycle**

The Milestone Decision Authority (MDA) in collaboration with the appropriate stakeholders determines if sufficient knowledge is obtained at each phase of the acquisition life-cycle before proceeding to the next phase. It is important to note that the initial phase of evolutionary acquisitions is preceded by Material Development Decision phase. An acquisition program can begin at any stage of the acquisition life-cycle, but it must meet the entrance criteria to enter the next phase. Therefore, if a program that is conceived after milestone B of the acquisition process framework, a technology readiness assessment must be conducted to ensure that the technologies meet the requirement for the upcoming phase [4, 5, 16].

### C. Technology Readiness Assessment (TRA) Process

The DODI 5000.2 establishes the requirement for the performance of Technology Readiness Assessment (TRA) in any defense acquisition program. The TRA is a systematic, metric-based process that evaluates the maturity of Critical Technology Elements (CTEs) of a system and is accompanied by a report that identifies how the CTEs are selected, and why are considered critical. TRA is not intended to assess the quality of the system architecture, design, or integration, but only reveal the readiness of critical system components based on what has been accomplished to date [5].

The DoD requires that readiness assessment shall be performed on Critical Technology Elements (CTE), prior to milestone B and C of the acquisition life-cycle. The process for performing a TRA is depicted in figure 3 [17]:

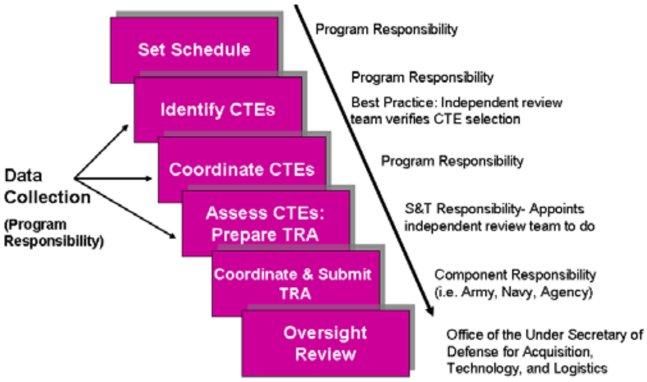


**Figure 3: Technology Readiness Assessment Process**

The process outlined in figure 3 begins with the development of the program schedule for meeting various milestones to successfully achieve program goals and objectives. The TRA process is initiated once CTEs of the system have been identified by examining all components across the Work Breakdown Structure (WBS). CTEs must be both essential to the system and either new and novel or used in a new or novel manner. Once the CTEs have been identified, data concerning their performance is collected and presented to an independent team who is expert in the technologies. Using the TRL metric, the independent review team assesses the maturity of the CTEs and seeks the approval of the S&T Executive, then submits the results to the Deputy Under the Secretary of Defense (Science & Technolog) DUSD(S&T) [5].

Once submitted three types of decisions can occur- DUSD(S&T) concurs with the TRA, concurs with reservation, or does not concur, which then the TRA is returned to the Service or Agency [5, 17]. If the DUSD(S&T) does not concur with the results, it either requests another technical assessment or sends the result back to the agency for changes. Further, DUSD(S&T) forwards the resulting recommendations to the Milestone Decision Authority (MDA) to support the acquisition decision process. The MDA ensures that the appropriate TRL is achieved prior to each milestone [5, 17, 18].

The MDA ensures that the entrance criteria of achieving the appropriate TRL prior to each milestone are met. All CTEs must attain TRL 6 prior to Milestone B and TRL 7 prior to Milestone C. The program will not advance to next Milestone if the preceding criteria are not met, therefore MDA must either restructure the program to use only mature technologies; delay the program start until all the technologies have adequately matured; modify the program requirements; request a Technology Maturity Plan (TMP) that describes the rational for proceeding to the next phase [5, 17]. In special circumstances, the DoD may grant a waiver for national security reasons [17].

## III. Maturity Assessment Methods

Technology maturity assessment is an avenue that engineers and program managers utilize to make critical decisions about the probability that a technology can contribute to the success of a system [13]. There has been a significant amount of research done to develop tools and methods that can provide insight into technology readiness and track technology maturity through the progression of system development life cycle in order to provide continuous risk management and enhanced decision support. Although the government and defense industry has widely adopted Technology Readiness Level (TRL) as a knowledge-based approach, this metric has been considered insufficient. The proposed approaches either expand on the TRL or integrate other metrics with the TRL to provide insight into technology and system readiness and maturity.

### *A. Technology Readiness Level (TRL)*

Technology Readiness Level (TRL) is a metric that was initially pioneered by the National Aeronautics and Space Administration (NASA) Goddard Space Flight center in the 1980's as a method to assess the readiness and risk of space technology [2, 14, 19-24]. Over time, NASA continued to commonly use TRLs as part of an overall risk assessment process and as means for comparison of maturity between various technologies [24]. NASA incorporated the TRL methodology into the NASA Management Instructions (NMI) 7100 as a systematic approach to technology planning process [24, 25]. The DoD along with several other organizations later adopted this metric and tailored its definitions to meet their needs.

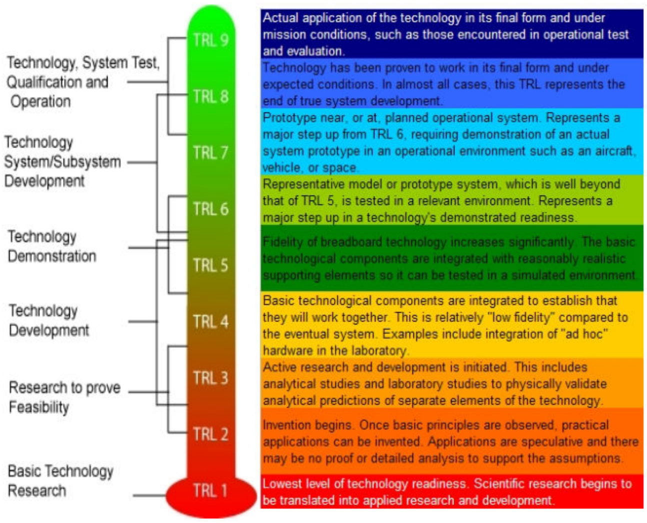


**Figure 4: DoD TRL Definitions**

In contrary to the well intention of the TRL metric to improve technology acquisition and transition into systems, literature indicates that it can in fact introduces risks because of its various insufficiencies including the lack of standard guidelines for implementing TRLs [26, 27]. These flaws, as discussed in the next section, can potentially convey a false sense of achievement with respect to maturation of technology. As a result, more robust and objective methods of assessing technology maturity are desired in order to make well informed procurement decisions.

### *B. TRL Limitations*

While the TRL metric is sufficient at its very basic level in evaluating technology readiness, it is considered deficient in various areas. Sauser et al. claim that the TRL index does not take into account the integration of two technologies [9-12, 23]. They believe that this metric lacks the means of determining maturity of integration between technologies and their impact on a system. Since it is highly probable that systems fail at integration point, Sauser et al. perceive the assessment of integration maturity as critical to the overall system success[9-12, 23].

Further, it is mandatory by legislative and regulatory laws that DoD technologies must be assesses with respect to their maturity throughout an acquisition process. However, the problem associated with the use of TRL is that there is no "how to" guideline when implementing the metric in a program. The DoD Interim Guidance simply states that "TRLs (or some equivalent assessment) shall be used" and no further detail is provided [14, 26].

Mahafza (2005) argues that the TRL metric is insufficient because it does not "measure how well the technology is performing against a set of performance criteria." She claims that the TRL methodology rates the maturity of a technology on a subjective scale and that it not adequate to label a technology as highly or lowly mature. Moreover, Smith (2004) notes that TRLs fall short in technology maturity assessment because it combines together multiple components of readiness into a single number; lacks the ability to systematically weight in the criticality of each technology to the entire system; and inability to account for the relative contribution of various readiness components throughout the system life cycle [24].

Cornford et al. (2004) assert that although the TRL provides a high level understanding of technology maturity, it lacks accuracy and precision. More accurate description of technology readiness is needed in order to make strategic decision at critical program junctures in order to prevent cost overruns and schedule delays. Cornford et al. (2004) describe the five limitations of the TRL method of assessing technology maturity as the following [2]:

- Subjective Assessment - there exist no formal method of implementing TRLs; the TRL value is assigned to technology by a technology developer who may be biased; the definitions of each TRL level is prone to broad interpretation.

- Not focused on system-to-system integration - TRLs focus on a component of a technology and when infusing the particular component with other in a larger scale, imperative integration concerns come forth.

- Focused on hardware and not software - at the time that the TRLs were conceived at NASA, hardware was emphasized significantly more than software.

- Not well integrated into cost and risk modeling tools - errors in incorrectly assigning TRL levels to a technology will inversely affect cost and risk models that have embedded in them means of reflecting technology maturity.

- Lacking succinct definition of terminology - the definitions of each TRL level can be ambiguous and reliant on an individual's interpretation. For example, defining the "relevant environment" to advance technology to TRL 6 is problematic because there are various environments that can be simulated such as low-gravity, radiation, temperature, vacuum etc.

According to the Office of the Under Secretary of Defense for Acquisition, Technology and Logistics, the TRL conveys the status of technology readiness on a scale only in a particular point in time. However, it does not communicate the possibility and difficulty of further maturing technology to higher TRL levels. The Office of the Under Secretary of Defense for Acquisition, Technology and Logistics also pointed out that the TRL is a "single axis, the axis of technology capability demonstration," therefore it does not give a complete picture of risks in integrating a technology into a system. In order to acquire a full understanding of the readiness and maturity of technology in a program, a multi-dimensional metric is necessary [28].

All in all, literature argues that core issues with the TRL method of assessing technology maturity include combining many dimensions of technology readiness into one metric [24]; not evaluating the uncertainty of maturing and integrating technology into a system [22-24, 29]; overlooking integration between two technologies [9-12, 23]; overlooking obsolescence and the probability of meeting requirements by a less mature technology [13]; and the inability to meet the need for a common platform for a system development and technology insertion [9-12, 23].

## IV. TOOL AND METHODS TO SUPPORT DECISION MAKING

The TRL metric has served as the primary maturity assessment tool since first incepted by NASA and later adopted by the DoD. With the drastic increase in system complexity in the recent years, this traditional maturity assessment technique has become incapable of meeting customer demands in both hardware and software intensive programs. Although the TRLs have been tailored by the DoD to better support defense acquisition, it lacks objectivity which result in overreliance on tacit knowledge.

Further, the TRLs were adequately meeting NASA's needs because NASA built systems in smaller quantity compared to DoD's large scale production. The problem arises with testing and integration of complex systems produced in large quantities, which introduces many uncertainties. NASA has no real way to measure maturity until they launched technology into space, whereas the DoD could recreate the relevant environment and perform their development and operational testing. As a result, the TRLs are insufficient because they do not take into account many of DoD's system development needs such as manufacturing, integration, transition, difficulty of advancing maturity and more.

To offset some of these issues, other models, tools, and methods have been developed. Some have been developed with the intent of introducing objectivity, while others have been developed to address the overlooked facets of technology development that have not been addressed by the TRLs. Due to variation in acquisition programs, resources, requirements, funding, schedule, and other program specific attributes, no one maturity assessment method fits all. As a result, using the Strength Weakness Opportunity Threat (SWOT) model this paper reviews and analyzes an assortment of maturity assessment models to enable technologists and acquisitionists to select the one that best fits their program. SWOT Analysis is a strategic assessment technique that will be used to evaluate the strengths, weakness, opportunity, and threat of maturity assessment models presented in this paper.

### *A. Qualitative Techniques*

The TRL metric was primarily designed to aim at hardware components. Attempts to leverage the qualitative nature inherent to TRLs in order to develop other definition-based scales specific to various disciplines have been made. A description of these methods is presented in figure 5. These techniques are considered qualitative by the author due to their descriptive nature defining each tier on the scale. Their descriptive natures make these metrics subjective techniques that oversimplify many facets of maturity and readiness into one value. In addition, the meaning behind the description of each tier is subject to personal interpretation. The methods listed in table 5 have one major common factor, which is that they are all a one dimensional yardstick on a scale of 0 – XX, with each level defining the degree of technology maturity.

Note that not all the metrics listed in figure 5 measure technology readiness, but instead leverage the concept of TRL to provide alternate venues to gauge other facets of product development. For instance, the MRL and the IRL metrics provide insight into manufacturing process maturity [5, 30, 30] and systematically assess the integration maturity of one technology to another [11, 31], respectively. Similar to the TRL, the MRL and IRL are a set of definitions divided into multiple levels, therefore these metrics also possesses the TRL limitations including subjectivity, imprecision, ambiguity, and incompleteness. A holistic method or tool that incorporates the TRL, IRL, and MRL would be of high value to determine the transition readiness of technology from the development phase to the system development phase. In fact the GAO contends that GAO contends that the DoD should develop a strong, disciplined approach to determine the transition readiness of its technologies [32]. Technology maturity is not the only determinant of transition readiness- factors such as cost, manufacturability, integration readiness, schedule are critical to support decisions regarding technology transition.

In general, gauging the maturity of technology and systems provide decision support with respect to advancing from one phase of the acquisition life-cycle to the next, however the difficulty of maturity advancement is also of high value to decision makers. As a result, the RD3 and AD2 metrics were developed to evaluate the difficulty of proceeding from the current maturity state to the desired state. Incorporating the information captured by these two metrics together with the TRL can provide a more depth understanding to the acquisition challenges and risks then the TRL alone.

The SWOT analysis of the qualitative maturity assessment tools, figure 6, reveals that one of the major shortfalls of qualitative metrics is that each one alone is not enough to provide a holistic understanding of the challenges surrounding complex systems. Each one may be adequately applicable to stand alone technologies, but complex systems comprised of multiple technologies that interact with one another are difficult to be assessed by methods such as the TRL.

| Tool | Description |
|---|---|
| **Qualitative Techniques** | |
| Manufacturing Readiness Level (MRL) | The MRL is a 10 level scale used to define current level of manufacturing maturity , identify maturity shortfalls and associated risks, and provide the basis of manufacturing maturation and risk management (Cundiff 2003). |
| Integration Readiness Level (IRL) | The IRL is a 9 level scale intended to systematically measure the maturity, compatibility, and readiness of interfaces between various technologies and consistently compare interface maturity between multiple integration points. Further, it provides a means to reduce the uncertainty involved in maturing and integrating a technology into a system (Gove 2007). |
| TRL for non-system technologies | Expansion of the TRL definitions to account for non-system technologies such as processes, methods, algorithms, and architectures (Graettinger et al 2002). |
| TRL for Software | Expansion of the TRL metric to incorporate other attributes specific to software development (DoD TRA Deskbook 2005). |
| Technology Readiness Transfer Level (TRRL) | The TRRL is a 9 level scale describing the progress of technology transfer to a new application. It expands and modifies the TRL definitions to address the transfer to space technology into non-space system (Holt 2007) . |
| Missile Defense Agency Checklist | A tailored verstion of the TRL metric specifically in support of hardware maturity through the development life-cycle of the product (Mahafza 2005). |
| Moorhouses Risk Versus TRL Metric | A 9 level metric mapping risk progression analogous to technology maturity progression. The TRL descriptions are tailored specifically toward UAV (Moorehouse 2002). |
| Advanced Degree of Difficulty (AD2) | Leveraging the concept of RD3, the AD2 augments TRLs by assessing the difficulty of advancing a technology from its current level to a desired level on a 9 tier scale (Bilbro 2007). |
| Research and Development Degree of Difficulty (RD3) | The RD3 is a 5 level scale intended to supplement the TRL by conveying the degree of difficulty involved in proceeding from the current TRL state to desired level, with 5 being very difficult and 1 being least difficult to mature the technology (Mankins 1998). |

**Figure 5: Qualitative Maturity Assessment Techniques**

Although quick and iterative, qualitative metrics highly rely on tacit knowledge, and therefore are subjective. While they idea of definition-based metrics enables flexibility and ease of use, the descriptions can be broadly interpreted leading to inaccurate assessment. Further, the items listed in figure 5 are soft metrics that lead to subjective maturity assessment.

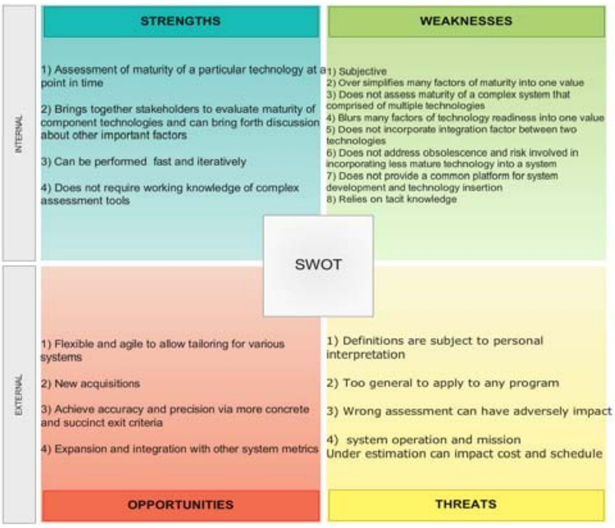


**Figure 6: Qualitative Techniques SWOT**

### *B. Quantitative Techniques*

The push to field systems in less time, less cost, and without jeopardizing system reliability and mission objectives has emphasized the need for more sophisticated methods and tools to assess maturity of complex technologies and systems. Attempts have been made to develop quantitative techniques to accurately and precisely provide insight into technology maturity, which in essence is a programmatic risk. The necessity to develop a tool that is both robust and objective is imperative to spending DoD dollars efficiently when procuring weapons systems. A review of quantitative techniques discovered during the literature review is presented in figure 7.

The techniques presented in figure 7 have one major common factor- each one provides insight into technology maturity through a mathematical model. The output of the quantitative techniques is derived from mathematical operations between two or more system metrics, and therefore the output value is not always indicative of technology or system maturity, but rather of the risk involved in developing the product. For example, the ITAM model quantifies the cumulative "system challenge" based on the "technological challenge" of its constituent technologies [22]. The "challenge" is analogous to the term risk and maturity is a measurement of risk. The more mature the technology, the less the risk. The maturity of products is evaluated in order to seek awareness into the risk and challenge in developing the technology.

The TRL Schedule Risk Curve, on the other hand, leverages the TRL metric to identify the appropriate schedule margin in order to mitigate the risk of schedule slips [20]. In addition, it can be used to evaluate whether a particular product can mature along a timeline. Although this model is not intended to assess technology maturity, it incorporates the TRL to assess cost risks.

The System Readiness Level (SRL) model is a quantitative method providing insight into system maturity [10, 11, 23]. Each technology in a system that is comprised of multiple technologies is connected to a minimum of one other technology. This network of technologies and their interfaces constitute the SRL matrix as a function of TRL and IRL. Moreover, the SRLmax is a mathematical model intended to maximize the SRL under constraint resources. The objective of the SRLmax is the achievement of the highest possible SRL based on the availability of resources such as cost and schedule [23].

Making accurate assessment of technology readiness and risks during the development life cycle enables success for a program. Mankins (2007) present a solution that integrates TRLs and risk assessment matrix known as Technology Readiness and Risk Assessment (TRRA) [21]. TRRA expands on the standard risk matrix by incorporating TRLs, the degree of difficulty of moving a technology from one TRL to another, and Technology Need Value (TNV) to map probability of failure of an R&D effort against the consequence of failure. The probability of failure is analogous to the degree of difficulty of moving a technology from one TRL to the next; therefore the lower the probability of failure, the lower the degree of difficulty. The TRRA forecasts the impact of various maturity levels on the risk of failure of the program.

| Tool | Description |
|---|---|
| **Quantitative Techniques** | |
| System Readiness Level (SRL) | The SRL is a normalized matrix of pair-wise comparisons of TRLs and IRL of a system. It is a quantitative method providing insight into system maturity as a product of IRL x TRL (Sauser et al. 2006, 2007, 2008) . |
| SRL Max | The SRL Max is a quantitative mathematical model aiming to maximize the SRL under constraint resources. The objective of the SRLmax is the achievement of the highest possible SRL based on the availability of resources such as cost and schedule (Ramirez-Marquez et al. 2009). |
| Technology Readiness and Risk Assessment (TRRA) | TRRA is a quantitative risk model that incorporates TRLs, the degree of difficulty (RD3) of moving a technology from one TRL to another, and Technology Need Value (TNV). The TRRA expands the concept of the risk matrix by integrating "probability of failure" on the y-axis and "consequence of failure" on the x-axis (Mankins 2007). |
| Integrated Technology Analysis Methodology (ITAM) | ITAM is a quantitative mathematical model that integrates various system metrics to calculate the cumulative maturity of a system based on the readiness of its constituent technologies. The system metrics include TRLs, delta TRL, R&D Degree of Difficulty (R&D3), and Technology Need Value (TND) (Mankins 2002). |
| TRL for Non-Developmental Item (NDI) Software | A mathematical method to assess the maturity of Non-Developmental Item (NDI) software using orthogonal metrics in combination with a pair-wise comparison matrix to examine two equivalent technologies that are candidate for insertion into a system. Incorporate other attributes such as requirement satisfaction, environment fidelity, criticality, product availability, and product maturity (Smith 2004). |
| Technology Insertion (TI) Metric | TI involves the integration of various metrics that deal with insertion of technology and subsystems into a current system in order to develop an "enhanced system." The TI Metric is a high level metric computed from sub-metrics or dimensions intended to evaluate the risk and feasibility of technology insertion from a subsystem and a system level (Dowling and Pardo 2005). |
| TRL Schedule Risk Curve | This is a quantitative model that does not communicate the maturity of technology at a certain point in time but instead leverages the TRLs metric to identify the appropriate schedule margins associated with each TRL level in order to metigate schedule slipps (Dubos et al. 2007). |

**Figure 7: Quantitative Maturity Assessment Techniques**

The SWOT in figure 8 reveals that although the quantitative techniques listed in figure 7 are relatively objective and precise compared to qualitative techniques in table 5, they may be time consuming and difficult to perform reiteratively. As a result of their mathematically integrative nature, quantitative techniques can be intimidating and discouraging to use when assessing technology maturity. They are also prone to mathematical miscalculation that can lead to wrong maturity assessment, cost overrun, and schedule delay. On the other hand, quantitative techniques integrate multiple system metrics, which result in tangible outputs to accurately support decision-making.

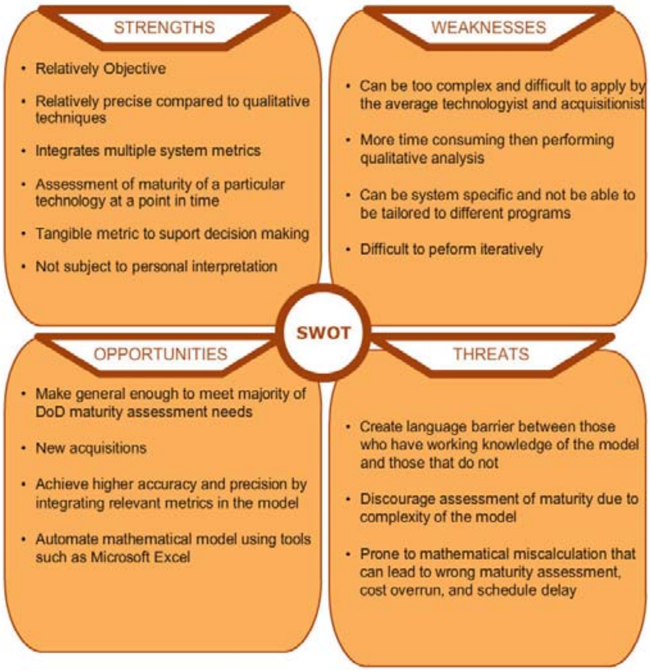


**Figure 8: Quantitative Techniques SWOT**

### *C. Automated Techniques*

In addition to qualitative and quantitative techniques, maturity assessment approaches fall into a third category referred to in this paper as automated techniques, described in figure 9. Automated techniques evaluate maturity of technology and systems using a tool that is directed by technologists and acquisitionists. The user feeds the tool information that is used to generate an output indicative of the maturity of the product. These techniques may perform quantitative analysis in the background, but the user does not need to perform any calculations.

The TRL calculator, pioneered by the Air Force Research Laboratory (AFRL), is a Microsoft excel based tool [14, 26], which makes it an automated technique. The calculator computes a TRL level based on the answers to a series of questions by the user and displays the output graphically [14]. The MRL calculator is based on the same concept of answering questions, however generating a MRL value.

The UK MoD SRL is an excel-based tool that captures key project outputs at nine levels of product development depicted in a systems engineering V-model and tracks system maturity on scale of 1-9. Each tier of the SRL scale is defined by a description, which adds a qualitative twist to the tool. The TPMM, on the other hand, is a framework that is divided into six phases that are mapped to the first six TRL levels. Each TPMM phase incorporates a set of goals, deliverables, and exit criteria to help determine whether a program should advance to the next stage (SMDTC 2006). The TPMM method is not purely quantitative or qualitative; therefore it is not listed in tables 5 or 7. It is a set of steps and criteria to provide guidance for the advancement of an acquisition. TPMM is considered an automated technique because it leverages a database to track the technical progression of the program from one phase to the next. The database enables user an autonomous interface to evaluate program advancement.

| Tool | Description |
|---|---|
| **Automated Techniques** | |
| Technology Readiness Level (TRL) Calculator | Microsoft excel based tool that enables the application of the TRL definitions to technology development. The calculator computes a TRL level based on the answers to a series of questions by the user and displays the output graphically (Nolte 2004). |
| Manufacturing Readiness Level (MRL) Calculator | Microsoft excel based tool that enables the application of the MRL definitions to technology development. Computes the MRL level based on answers to a series of questions in various threads related to manufacturing readiness. |
| Technology Program Management Model (TPMM) | TPMM is a technology-development activity model, partitioned into phases that are gate qualified using the TRLs. The model defines each TRL as a stage and establishes exit criteria (gate) for each stage of TRL. Each TRL stage has an associated checklist of activities that must be achieved before succeeding to the next stage. The TPMM is comprised of seven technology development phases (SMDTC 2006). |
| UK MoD Systrem Readiness Level | Captures key outputs from th nine levels of product development depicted by the Systems Engineering V-model in an excel-based tool. These outputs are confined and tracked in a matrix. Each output is evaluated on a 9 level SRL scale (http://www.ams.mod.uk/aofcontent/tactical/techman/content/srl_whatarethey.htm) |

**Figure 9: Automated Maturity Assessment Techniques**

The SWOT analysis of automated techniques depicted in figure 10 reveals many attributes that are shared by the quantitative and qualitative techniques. For example, these techniques evaluate the maturity of a product at a given time, but do not convey details about the potential of maturity improvement, the risk involved in improving to a higher maturity, and the probability of advancing the maturity level. They are more objective than the qualitative metrics because the result is calculated based on answers to a series of questions, which in essence incorporate information about design and development risks. Further, they make the process of calculating maturity of a product more repeatable and allow for more consistent comparison of different technologies based on its standard set of questions.

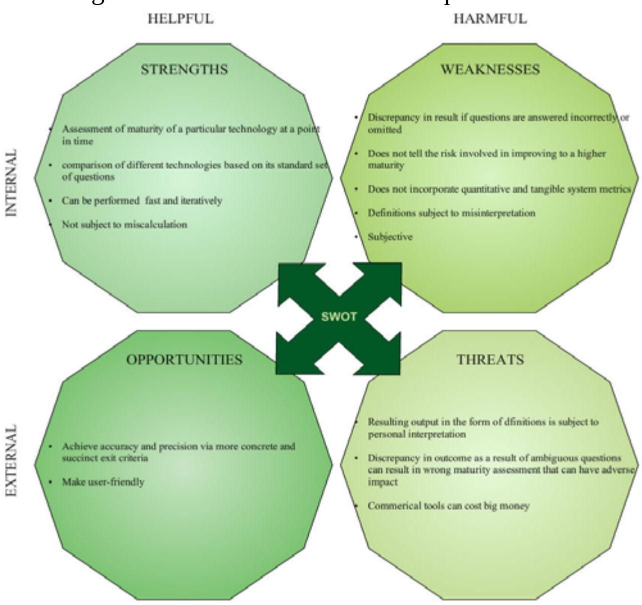


**Figure 10: Automated Techniques SWOT**

The SWOT also conveys that although automated maturity assessment technique can be performed fast and iteratively, discrepancy in result can occur if questions are answered incorrectly or information is omitted. For instance, with reference to the TPMM framework, if the user inputs the wrong data or accidentally deletes data from the database, it will appear as adverse impact to the program. Likewise, if questions are answered incorrectly using the TRL calculator, the wrong readiness level value will result. Further, they can achieve precision and accuracy by incorporating quantitative and tangible system metrics. Discrepancy in outcome of maturity assessment as a result of ambiguous questions can result in wrong can have adverse impact on a program.

## V. Conclusion

This paper contends that objective and robust methods that can assess technology maturity accurately and provide insight into risks that lead to cost overruns, schedule delays, and performance degradation are imperative for making well-informed procurement decisions during any defense acquisition. The current DoD standard maturity assessment tool, the TRL metric, evaluates the readiness of technology at an instant of time and therefore does not predict the performance of the technology or evaluate the quality of the system architecture, design, and integration. Realizing this challenge, this paper introduced and summarized numerous other models and methods that have been developed to either complement the TRL or provide new means of evaluating technology maturity in order to mitigate risks in cost, schedule, performance, operation, and acquisition of defense systems.

This paper brought forward a gap in literature with regards to the interchangeable utilization of readiness versus maturity, as well as system versus technology. Readiness and maturity have been used interchangeably in literature to characterize the developmental progress of products. Moreover, with the increasing complexity of systems, many of the approaches recently developed to assess maturity and readiness are exclusive to systems.

Measuring technology maturity is critical because it can be used to establish milestone and track progress, provided entry and exit criteria for various milestones, and provide insight into risk and establish urgency to develop risk management plans. Using a SWOT (Strength, Weakness, Opportunity, Threat) analysis, this paper categorizes the maturity assessment tools and metrics into three groups including, qualitative, quantitative, and automated. It is necessary now to have the acquisition community utilize these tools and provide feedback with respect to the SWOT fields.

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