A system maturity index for the systems engineering life cycle

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Abstract: In the United States (USA) National Aeronautics and Space Administration (NASA) and the USA Department of Defense (DoD) the Technology Readiness Level (TRL) scale is a measure of maturity of an individual technology, with a view towards operational use in a system context. A comprehensive set of concerns becomes relevant when this metric is abstracted from an individual technology to a system context. This paper proposes the development of a system-focused approach for managing system development and making effective and efficient decisions during a systems engineering life cycle. This paper presents a System Readiness Level (SRL) index that incorporates both the current TRL scale and an Integration Readiness Level (IRL) and provides a method for determining readiness of a system in the systems engineering life cycle. This paper concludes with a general discuss of the implication of the proposed SRL and how this may be applied to four case examples.

Keywords: SRL; system readiness level; TRL; technology readiness level; IRL; integration readiness level; systems engineering life cycle.


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1 Introduction

In theory, technology and system development follow similar evolution (or maturation) paths; a technology is inserted into a system (e.g. spiral development) based on its maturity, functionality and environmental readiness and ability to interoperate with the intended system. However, the assessments made during the systems engineering life cycle that support these decisions are not always effective, efficient or well developed (Lorell et al., 2006). Recently, the Government Accountability Office stated that many of the programs in the United States (USA) Department of Defense (DoD) plan to hold design reviews or make a production decision without demonstrating the level of technology maturity that should have been there before the start of development.
A system maturity index for the systems engineering life cycle

(GAO, 1999). In many USA government agencies and contractors, Technology Readiness Level (TRL) is used to assess the maturity of evolving technologies (materials, components, devices, etc.) prior to incorporating a technology into a system or subsystem. In the 1990s the USA National Aeronautics and Space Administration (NASA) instituted this nine level metric as a systematic metric/measurement approach to assess the maturity of a particular technology and to allow consistent comparison of maturity between different types of technologies (Mankins, 2002). Given the pragmatic benefits of this concept, in 1999, the DoD embraced a similar TRL concept (DoD, 2005a,b). While the use of TRL is similar in these organisations, TRL was not intended to measure the integration of technologies, but as an ontology for contracting support (Sadin et al., 1989). The application of ontology metrics to support integration has been extensively used in the computer industry to define coupling of components (Orme et al., 2006, 2007), but a common ontological approach to technology integration for system development has been far less developed. While some have attempted to use TRL for this purpose, it has been shown that TRL does not address:

- a complete representation of the (difficulty of) integration of the subject technology or subsystems into an operational system (Dowling and Pardoe, 2005; Mankins, 2002; Meystel et al., 2003; Smith, 2005; Valerdi and Kohl, 2004)

- the uncertainty that may be expected in moving through the maturation of TRL (Cundiff, 2003; Dowling and Pardoe, 2005; Mankins, 2002; Moorehouse, 2001; Shishko et al., 2003; Smith, 2005)

- comparative analysis techniques for alternative TRLs (Cundiff, 2003; Dowling and Pardoe, 2005; Mankins, 2002; Smith, 2005; Valerdi and Kohl, 2004).

Based on these fundamental conjectures, a more comprehensive set of concerns becomes relevant when TRL is abstracted from the level of an individual technology to a system context, which usually involves the interplay among multiple technologies. 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 (Nambisan, 2002; Watts and Porter, 2003). Similarly relevant is the case where these technologies are integrated through the systems engineering life cycle. That is, component level considerations relating to integration, interoperability and sustainment (e.g. producibility, supportability and evolvability) become equally or more important from a systems perspective in an operational environment (Sandborn et al., 2003).

In summary, technology integration as part of a systems engineering life cycle needs a quantitative assessment tool that can determine whether a group of separate technology components with their associated (and demonstrated) TRL ratings can be integrated into a larger complex system at a reasonably low risk to perform a required function or mission at some performance level (Rowell and Braun, 1999). For simple systems, it is not impossible to subjectively assess their stage of development; however, for the current size and complexity of many of today’s systems, an objective and repeatable method is highly needed (Graettinger et al., 2002).

To address these concerns, this paper focuses on the development of a System Readiness Level (SRL) index that incorporates the maturity level of specific components, and the interoperability of the entire system (Sauser et al., 2006). This SRL is achieved by incorporating the current TRL scale and the concept of an Integration Readiness Level (IRL). By using TRL to measure the maturity of each component technology and IRL to
measure the integration of any two TRL assessed technologies, the SRL can be determined as a function of TRL and IRL. The resultant SRL index can provide an assessment of overall system development and prioritise potential areas that require further development. This new index can then interact 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), system life cycle cost, and system maturity (measured by SRL). The overarching perspective of this paper provides a context for the ‘trade space’ available to a systems engineer or program manager along with the articulation of the overall objective of maximising the operational effectiveness of systems.

2 Metrics for technologies, integrations and systems

The use of metrics in project management and system engineering has been a proven and successful practice in most organisations. As a benchmark in decision making, they can perform an integral part of management activities for indicating performance or effectiveness of risk, quality and maturity. More specifically metrics can:

• identify critical parameters
• establish milestones to assess progress
• provide direction for risk management/mitigation
• sustain entry and exit criteria for major milestones.

Despite the wide use of metrics, they must follow some simple rules, as defined by Dowling and Pardoe (2005), so they can be effective and efficient in an organisation:

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 way 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).

With these simple, yet critical, rules to develop metrics, the next step is to determine exactly what kind of metrics will be used. There are fundamentally two kinds of metrics, hard metrics which are measured objectively through data analysis and soft metrics which are measured through a subjective judgement. Hard metrics are generally more difficult to derive due to the need for data, while soft metrics are relatively easy to derive, but require a complementing rational that explains the assessment (Dowling and Pardoe, 2005). For the developments of a systems readiness level and its associated metrics, we considered the rules defined by Dowling and Pardoe for the development of a soft metric which could be universally understood and used. The following sections will explain the systems readiness level index and its associated metrics.
2.1 Technology readiness level

From being a seven level metric instituted by NASA in the 1980s, TRL is now a nine level metric and a concept that is used widely across NASA and DoD to measure the maturity of a technology and also to compare maturities of different technologies. Despite earlier work by Mankins (2002), there have been only three other independent efforts to expand or enhance the TRL metric. Firstly, the DoD introduced the concept of Manufacturing Readiness Levels (MRL) to expand TRL to incorporate producibility concerns related to risks associated with time and manufacturing. MRLs are a metric that assesses the system engineering/design process and maturity of a technology’s associated manufacturing processes to enable rapid, affordable transition to acquisition programs. The MRL index is used early in the development phase for acquisition program managers to comply with the DoD 5000.1 mandates (Cundiff, 2003). Second has been the work of Smith (2005) at Carnegie Mellon Software Engineering Institute who expanded TRL to include additional readiness attributes of requirements satisfaction, environmental fidelity, criticality, product availability and product maturity to define an evaluation framework of similar technologies. The third and most extensive developments have been by the UK Ministry of Defence (MoD). Based on concerns for successful insertion of technology into a system, they have developed a Technology Insertion Metric that includes TRL, a Systems [Integration] Readiness Level and Integration Maturity Level (Dowling and Pardoe, 2005). They have then correlated systems engineering practices for each index based on phases in the systems engineering life cycle and MoD Policy. While the efforts previously described have greatly expanded and enhanced our understanding of TRL, it is our premise that TRL is not an end state to determining a system’s readiness.

2.2 Integration readiness level

Integration is the process of assembling the system from its components, which must be assembled from their specified requirements (Buede, 2000). It seems to be a simplistic process of 'putting together' a system from its components, which in-turn are built from requirements which are readily identifiable to any systems engineer. Integration can be a complex process containing multiple overlapping and iterative tasks meant to not only 'put together' the system but create a successful system built to user requirements that can function in the environment it was intended.

This definition of integration implies a structure to system integration. This structure is often described in the systems engineering life cycle as being the 'upward slope' of the traditional V-model (Forsberg et al., 2005). It starts with implementation and ends with verification and validation of the complete system in the operational environment. Moving from simply integrating components to integrating the system into its relevant environment is a considerable effort that requires not only disciplined engineering, but also good management of the entire systems engineering life cycle.

TRL does not accurately capture the risk involved in the adopting of a technology, and any technology can have an architectural inequality related to integration (Smith, 2005; Valerdi and Kohl, 2004). As system’s complexity increases (e.g. a large
interconnected network) there must be a reliable method and ontology for integration that allows TRLs to collectively combine for developing potentially complex systems. To measure integration, we will describe an index (i.e. IRL) that can indicate how integration occurs. This index considers not only the physical properties of integration, such as interfaces or standards, but also interaction, compatibility, reliability, quality, performance and consistent ontology when two technologies are being integrated.

Considering the various limitations and inability of the TRL metric to effectively handle integrations in a system, a seven level IRL metric was suggested by Sauser et al. (2006). Following further research, the IRL advanced into a nine level scale with similar theoretical foundations as TRL (Gove, 2007; Gove et al., 2007). While there have been some efforts to develop metrics that can be used to evaluate integration (e.g. DoD, 1998; Fang et al., 2004; Mankins, 2002; Nilsson et al., 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 effectively determine a system maturity. IRL is a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points (i.e. TRLs). IRLs describe the integration maturity of a developing technology with another technology, developing or mature. The addition of IRLs not only provides a check to where the technology is on an integration readiness scale, but also a direction for improving integration with other technologies. As TRL has been used to assess the risk associated with developing technologies, IRL is designed to assess the risk of integration. Table 1 shows the nine levels of IRL and gives a definition and description of each level.

2.3 System readiness level

Although component TRLs are necessary for evaluating system risk and potential, they are generally insufficient. To address this insufficiency, a new composite metric, called a SRL has been defined as a quantifier to assess maturity for a potential system as a function of the current TRL for individual technology components and the complexity of integration or compatibility between those components (i.e. IRL) (Sauser et al., 2007). From this point, if every technology is assessed using TRL and the system architecture is used to build an integrated representation of the system (e.g. physical architecture, context diagram) in which integrations are assessed using IRL, a metric that provides an assessment of a systems maturity can be considered. The computation of this new metric, for example, can be a normalised matrix of pair-wise comparisons of TRL and IRL. Therefore, the SRL can be understood as an index of maturity from 0 to 1 applied at the system-level with the objective of correlating this indexing to appropriate systems engineering management principles. An illustration of the rationale under which SRL has been constructed is presented in Figure 1.
### Table 1  
Integration readiness levels

<table>
<thead>
<tr>
<th>IRL</th>
<th>Definition</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>9</td>
<td>Integration is <em>Mission Proven</em> through successful mission operations.</td>
<td>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.</td>
</tr>
<tr>
<td>8</td>
<td>Actual integration completed and <em>Mission Qualified</em> through test and demonstration, in the system environment.</td>
<td>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.</td>
</tr>
<tr>
<td>7</td>
<td>The integration of technologies has been <em>Verified and Validated</em> with sufficient detail to be actionable.</td>
<td>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.</td>
</tr>
<tr>
<td>6</td>
<td>The integrating technologies can <em>Accept, Translate and Structure Information</em> for its intended application.</td>
<td>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.</td>
</tr>
<tr>
<td>5</td>
<td>There is sufficient <em>Control</em> between technologies necessary to establish, manage and terminate the integration.</td>
<td>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.</td>
</tr>
<tr>
<td>4</td>
<td>There is sufficient detail in the <em>Quality and Assurance</em> of the integration between technologies.</td>
<td>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.</td>
</tr>
<tr>
<td>3</td>
<td>There is <em>Compatibility</em> (i.e. common language) between technologies to orderly and efficiently integrate and interact.</td>
<td>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.</td>
</tr>
<tr>
<td>2</td>
<td>There is some level of specificity to characterise the <em>Interaction</em> (i.e. ability to influence) between technologies through their interface.</td>
<td>Once a medium has been defined, a ‘signalling’ 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.</td>
</tr>
<tr>
<td>1</td>
<td>An <em>Interface</em> between technologies has been identified with sufficient detail to allow characterisation of the relationship.</td>
<td>This is the lowest level of integration readiness and describes the selection of a medium for integration.</td>
</tr>
</tbody>
</table>
3 SRL formulation

In any system, each of the constituent technologies is connected to a minimum of one other technology through a bi-directional integration. How each technology is integrated with other technologies is used to formulate an equation for calculating SRL that is a function of the TRL and IRL values of the technologies and the interactions that form the system. In order to estimate a value of SRL from the TRL and IRL values we propose a normalised matrix of pair-wise comparison of TRL and IRL indices. That is, for a system with $n$ technologies, we first formulate a TRL matrix, labelled $[TRL]$. This matrix is a single column matrix containing the values of the TRL of each technology in the system. In this respect, $[TRL]$ is defined in (1), where $TRL_i$ is the TRL of technology $i$.

$$[TRL]_{n 	imes 1} = egin{bmatrix} TRL_1 \\ TRL_2 \\ \vdots \\ TRL_n \end{bmatrix} \tag{1}$$

Secondly, an IRL matrix is created as a symmetric square matrix (of size $n 	imes n$) of all possible integrations between any two technologies in the system. For a system with $n$ technologies, $[IRL]$ is defined in (2), where $IRL_{ij}$ is the IRL between technologies $i$ and $j$. It is important to note that whenever two technologies are not planned for integration, the IRL value assumed for these specific technologies is the hypothetical integration of a technology $i$ to itself; therefore, it is given the maximum level of 9 and is denoted by $IRL_{ii}$.

$$[IRL]_{n 	imes n} = egin{bmatrix} IRL_{11} & IRL_{12} & \cdots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \cdots & IRL_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ IRL_{n1} & IRL_{n2} & \cdots & IRL_{nn} \end{bmatrix} \tag{2}$$
Although the original values for both TRL and IRL can be used, the use of normalised values allows a more accurate comparison when comparing the use of competing technologies. Thus, the values used in [TRL] and [IRL] are normalised (0, 1) from the original (1, 9) levels. Based on these two matrices, an SRL matrix is obtained by obtaining the product of the TRL and IRL matrices, as shown in (3).

\[ [SRL]_{n \times 1} = [IRL]_{n \times n} \times [TRL]_{n \times 1} \]  

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 TRL. Mathematically, for a system with \( n \) technologies, \([SRL]\) is as shown in (4).

\[
[SRL] = \begin{bmatrix}
SRL_1 \\
SRL_2 \\
\vdots \\
SRL_n
\end{bmatrix} = \begin{bmatrix}
IRL_{1,1}TRL_1 + IRL_{1,2}TRL_2 + \cdots + IRL_{1,n}TRL_n \\
IRL_{2,1}TRL_1 + IRL_{2,2}TRL_2 + \cdots + IRL_{2,n}TRL_n \\
\vdots \\
IRL_{n,1}TRL_1 + IRL_{n,2}TRL_2 + \cdots + IRL_{n,n}TRL_n
\end{bmatrix}
\]  

Each of the SRL values obtained in (4) would fall within the interval (0, \( n \)). For consistency, these values of SRL should be divided by \( n \) to obtain the normalised value between (0, 1). Notice that \([SRL]\) itself can be used as a decision-making tool since its elements provide a prioritisation guide of the system’s technologies and integrations. Thus, \([SRL]\) can point out deficiencies in the maturation process.

The SRL for the complete system is the average of all such normalised SRL values, as shown in (5). Equal weights are given to each technology and hence 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.

\[
SRL = \frac{\left(\frac{SRL_1}{n}\right) + \left(\frac{SRL_2}{n}\right) + \cdots + \left(\frac{SRL_n}{n}\right)}{n}
\]  

In the following section we present a sample SRL calculation and then apply the SRL method to real systems with a discussion of how SRL could provide value in evaluating the represented cases correlated to a systems engineering life cycle.

### 4 SRL application

#### 4.1 Example SRL calculation

The following example will use a simple system of three technologies and two integrations (see Figure 2) to show the steps involved in calculating the SRL value.

For this system the following matrices can be created for TRL and IRL as per definitions presented earlier:

\[
[TRL] = \begin{bmatrix} 9 \\ 6 \\ 6 \end{bmatrix} \quad \begin{bmatrix} 1.000 \\ 0.667 \\ 0.667 \end{bmatrix}
\]
Note that there is no integration between technologies A and C in this system and hence the integration $\text{IRL}_{ac} = 9$ as per definition.

The $\text{[SRL]}$ would be:

$$[\text{SRL}] = \begin{bmatrix} 1.7407 \\ 1.2963 \\ 2.1852 \end{bmatrix}$$

and finally,

$$\text{SRL} = \frac{(1.7407/3) + (1.2963/3) + (2.1852/3)}{3} = \frac{0.5802 + 0.4321 + 0.7284}{3} = 0.58$$

Figure 2   System with three technologies (A, B and C) with TRLs and IRLs

4.2 Case examples

Despite the utility of calculating a SRL, the SRL still has to have some correlation to quantitative systems engineering practices to provided added value in understanding its implication on the systems engineering life cycle. Using documented qualitative data, we were able to calculate the SRL for four case examples (i.e. Mars Climate Orbiter (MCO), ARIANE 5, Hubble Space Telescope (HST) – Service Mission, HST – Robotic Mission) and show how the SRL of these systems can be described using any of four standard systems engineering life cycles (i.e. Typical High-Technology System (Haskins, 2006), ISO 15288 (DoD, 2005a; ISO, 2002; NASA, 2007). These cases represented systems development successes and failures, levels of abstraction and views in retrospect. Table 2 summarises the cases with an evaluation of the TRL and IRL indices of the system of interest. In the following sections we present the calculated SRL for each case, map the SRL value against the four previously mentioned systems engineering life cycles (see Figure 3) and describe what the SRL value can tell us about each case.
Table 2  Case study descriptions and TRL/IRL evaluations (see online version for colours)

<table>
<thead>
<tr>
<th>Case description</th>
<th>System concept diagram</th>
</tr>
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<tbody>
<tr>
<td><strong>Mars Climate Orbiter (MCO):</strong> Robotic spacecraft sent to orbit Mars and collect data on Martian atmospheric conditions, and act as a communications relay for future missions. MCO failed due to impulse-bit data was assumed to be produced by the ‘Small Forces’ files in Newton-Seconds (N-s), whereas ‘Small Forces’ actually output in Pound-Seconds (lbs-s).</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="MCO Diagram" /></td>
<td></td>
</tr>
<tr>
<td><strong>ARIANE 5:</strong> Launch platform for delivering payloads into Earth Orbit. ARIANE 5 failed when an inertial Reference System failed 36.7 sec after launch due to a software exception caused by the rocket’s horizontal velocity, which was within thresholds, exceeding the limit of what the onboard-software could handle.</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="ARIANE 5 Diagram" /></td>
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<tr>
<td><strong>Hubble Space Telescope-SM-1:</strong> Servicing Mission (SM) to Hubble to correct the spherical aberration present on the primary mirror, and provide necessary support maintenance. SM-1 resulted in successful servicing of Hubble, a return to successful science operations and a safe return of shuttle crew.</td>
<td></td>
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<tr>
<td><img src="image" alt="HST-SM-1 Diagram" /></td>
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<tr>
<td><strong>Hubble Space Telescope-RSM:</strong> Service Hubble and other spacecraft using a robotic servicing craft thereby reducing cost and the risk to human life. A problem arose when the technology and concepts for RSM were unproven in space and a RSM seemed not to be feasible in time.</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="HST-RSM Diagram" /></td>
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</tbody>
</table>
4.2.1 Mars climate orbiter

MCO crashed into the Martian atmosphere on 23 September 1999. The Mishap Investigation Board (MIB) found the reason for the loss of the spacecraft to be the use of English units in a ground software file called ‘Small Forces’, the output of which was fed into another file called Angular Momentum Desaturation (AMD) which assumed inputs to be in metric, as were the requirements of the project. The MCO navigation team then used the output of this file to derive data used in modelling the spacecraft’s trajectory, and perform corrective thruster firings based upon these models. The Software Interface Specification (SIS) defined the format of the AMD file and specified that the data used to describe thruster performance, or the impulse-bit, be in Newton-Seconds (N-s) (Euler et al., 2001; JPL, 1996; NASA, 1999; Sauser, 2004, 2006).

For MCO, IRL alone can represent the basic problem, a misunderstanding of translated data. In addition, when reviewing the SRL for the system of interest on MCO, we calculate a SRL of 0.74. If we depict the SRL value against our four systems engineering life cycles, as depicted in Figure 3, we can get an indication of where the MCO system maturity was in relation to the systems engineering life cycle. The SRL value indicates that this system should have been in a product verification process that should inspect and test the system and effectively demonstrates that product integration conforms to its design solution against demonstrated measures of performance before the system could move into production and then operations. The MIB would later state that MCO had inadequate verification and validation of the failed system (NASA, 1999).
4.2.2 ARIANE 5

The ARIANE series of launch vehicles was developed by the European Space Agency (ESA) as a commercially available, low cost, and partially reusable solution for delivering payloads into Earth orbit. ARIANE 5’s maiden flight occurred on 4 June 1996 and ended 37 sec after liftoff, when the vehicle veered off of its flight path and disintegrated due to aerodynamic stress. In the following days an independent inquiry board was established to determine the cause of the failure. The board found that the failure began when the backup Inertial Reference System (SRI) failed 36.7 sec after H0 (H0 is the point at which the main engines were ignited for liftoff) due to a software exception. The incorrect thruster nozzle angles forced the launcher into an angle-of-attack that exceeded 20°, leading to aerodynamic stress that resulted in the booster engines prematurely separating from the main stage, which finally triggered the self-destruct of the main stage at approximately H0 + 39s (ESA, 1996; Jézéquel and Meyer, 1997; Lann, 1997; Lions, 1996).

The IRL recommends that there should be some form of integration control, otherwise one technology could dominate the integration, and this is exactly what occurred with ARIANE 5. When calculating the SRL for this system and matching it against the systems engineering process, an SRL of 0.67 indicates that the demonstrated system integration, interoperability, safety and utility may not have been addressed and the systems may not have achieved operational capability that would satisfy mission needs. At this phase the end product should begin to be transformed into a design solution through assembly and integration of lower level subsystems. The transition out of this phase is into a verification process based on defined requirements.

4.2.3 Hubble space telescope-SM-1

From its beginning the HST was envisioned as an upgradeable space observing platform, meaning that in addition to being the most detailed optical telescope in history, it was also built to carry additional science equipment, and was built such that this equipment could be added, replaced or maintained by an extra-vehicular activity event. In order to meet this requirement HST was a completely modular design, and the outer-shell even included such details as handholds for servicing astronauts. This modularity and upgradeability would soon prove their value as, after initial launch and the start of science operations, it was discovered that the primary mirror had an aberration that caused a blurring of far-off objects, the very objects that were HST’s primary objective to study. It seemed as though HST was a failure, however, in December 1993 the STS-61 crew was able to successfully attach Corrective Optics Space Telescope Axial Replacement (COSTAR) to correct the problem, in addition to performing other minor repairs such as fully unfolding a solar panel, tightening bolts and securing access doors. That mission was designated Servicing Mission – 1 (SM-1) (Lanzerotti, 2005; Mattice, 2005).

HST SM-1 demonstrates that IRL is able to identify a successful architecture. The integrations of the COSTAR and WFPC2 need to be matured further, but they must be integrated into the system and used in the mission environment in order to accomplish this, which is exactly what was done. When reviewing the SRL for this system, an SRL of 0.84 indicates this system should be in a phase of production and development while achieving operational capability that satisfies mission needs. This was the case for SM-1. What the SRL of 0.84 does indicate which can often be the case with many space
missions is that an SRL of greater than 0.8 become difficult when fully operational systems are unable to be test in their operational environment (i.e. space) before mission operation.

4.2.4 Hubble space telescope-RSM

After many years of exceptional service, NASA has been considering a technical solution to repairing the HST as it has far surpassed its expected lifetime. Its gyroscopes are approaching the end of their life cycle, its batteries are nearing their lower levels of acceptable performance and the fine-guidance sensors have already begun failing. If HST is not serviced soon and the batteries run out, or navigational and attitude control is lost, certain instruments aboard could be permanently damaged either due to low temperatures or direct exposure to sunlight. In order to repair HST NASA will have to perform a SM-4 to keep HST operating into the future. The problem is that HST has not been serviced since before the Columbia disaster and the Columbia Accident Investigation Board (CAIB) requirements for shuttle operations would impact a HST SM-4 since time and fuel considerations may not allow the crew to safely dock to the International Space Station (ISS) if damage is found on the heat shield. To combat this problem a Robotic Servicing Mission (RSM) has been suggested thereby reducing cost, and the risk to human life (Lanzerotti, 2005; Mattice, 2005). As an independent committee was established to determine the feasibility of this mission, we can evaluate the current state of the proposed RSM solution for its system maturity level.

Evaluating the SRL of this system allows us to look at a system that has not been deployed into operation. When reviewing the SRL for this system in its current state, an SRL of 0.65 indicates this system should be in a phase at which development is a system of increment of capability, system requirements are being refined and there should be an effort to reduce integration and manufacturing risk as well as ensure operational supportability with demonstrated system integration, interoperability, safety and utility.

In summary, two general observations of the SRL applied to the systems engineering life cycle are:

1. all systems will start at no less than 0.1, for no system can theoretically be 0.0 as soon as the concept is conceived
2. it is uncommon for any system to be SRL of 0.9 or greater, for most systems are deployed with some degree of technologies or integrations that are not fully mature.

In the next section we will discussion the potential implication for making systems engineering decisions during the systems engineering life cycle using the SRL.

5 SRL and potential implications to systems engineering

In the systems engineering life cycle there are factors that may strategically alter the decision to: develop one system over another; supersede a new, more functional system over another; determine if a system or technology has become inadequate due to changes in other systems or technologies; invest in the development of a new system or maintain existing systems and classify a systems obsolescence and longevity. While identifying
the current SRL of a system can provide managerial insight, optimising the future value of this index based on constrained resources will enhance managerial capabilities. Therefore, to address these challenges, we propose that SRL can be used as a method for determining current and future readiness of a system.

While the SRL calculates a value based on the present IRL and TRL values of the system, it is also possible to define a System Readiness Potential (SRP) to indicate future potential of the system. The IRL and TRL values may have potential for future growth based on their current level of maturity or could have a maximum ceiling constrained by the system or technology or any other factor. Considering these issues, a future value of IRL and TRL and hence a SRP can be calculated. For the calculation of the SRP, the mathematical approach would remain unaltered, yet, the understanding and perspective of the SRP value would be different. For determining the SRP it would be possible to perform sensitivity analysis on the TRLs and IRLs within the system of interest to analyse the SRL of the system due to an increase in one or more of the constituent technologies or integrations. For example, using the system represented in Figure 2 one could perform a sensitivity analysis to understand what impacts a change in an IRL would have on the SRL. Figure 4(a)–(c) show a projection of the SRL if we were to mature either of the IRLs. In this situation, we hold the TRLs constant assuming that we are designing a system where the technologies are not within the systems engineers’ control, and transferred over to the integration team and thus the TRL values of the technologies cannot be changed. The integration team therefore can only study the change in overall SRL of the system due to an increase in the IRL values. A similar analysis could be done with the TRLs.

Using this approach, an optimisation of SRL based on resource allocation can allow for decisions to be made regarding the trade-offs among:

1. system attributes such as availability, performance, efficiency and total ownership cost
2. the components necessary for producing affordable system operational effectiveness (Verma et al., 2003a,b).

These attributes have objectives and ranges for components such as capability, reliability, maintainability, supportability and producibility and it is the interplay among them that drives the different levels for both IRL and TRL of the elements in a system. Thus, the optimal selection of which components to enhance to improve the system’s SRL becomes a system development optimisation problem.

Sharma et al. (2007) showed the value that an optimisation approach can have to the systems engineer for analysing and predicting the uncertain behaviour of the system in a more realistic manner. From a systems engineering design perspective, an optimisation approach that balances needs (i.e. the enhancement of the SRL) with resources (i.e. cost of technologies, cost of technology development, etc.), can be an effective and efficient method for reducing risk. That is, the development of a SRL index correlated with a systems engineering process can be used as an optimisation framework for the systems engineer or program manager to design-in enhanced system reliability, maintainability and supportability to achieve the desired reductions in the necessary logistics footprint and the associated life cycle cost.
Figure 4  (a) IRL_{ab} sensitivity projections, (b) IRL_{bc} sensitivity projections and (c) SRL sensitivity projections
6 Conclusions and future work

The purpose of this paper is to provide system designers and developers as well as program and project management a common metric, process, framework, and format for managing system development and effective and efficient decision-making during the systems engineering life cycle. This paper not only described how these metrics are determined, but how they can be integrated within the systems engineering process. In addition, the knowledge created from this research can be extended to develop maturation plans/tools for future acquisition strategies. In summary, this knowledge can provide:

- the ability to collectively evaluate component integration and system readiness to reduce systems engineering life cycle risks
- a fast and dynamic assessment platform with a set of rules, guidelines and ontology for consistency, repeatability and traceability during the systems engineering life cycle
- the ability to consider system obsolescence through comparative analysis of multiple technologies in trade studies or spiral development – Cause and Effect? Consequences?
- a decision-making approach to allow optimal design variants (different designs, same architecture).

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References


A system maturity index for the systems engineering life cycle


