# Monte-Carlo Simulation Approach for System Readiness Level Estimation

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**Abstract**. A system-focused prescriptive metric, called System Readiness Level (SRL), which incorporates both the current Technology Readiness Level (TRL) scale and the concept of an Integration Readiness Level (IRL) has recently been established to measure current and future readiness status of a system under development. In previous research, deterministic values for components' TRLs and IRLs estimation were assumed, which involves much human subjectivity. Moreover, only point estimation from calculation was proposed in previous research. In order to reduce the subjective influence, we propose a probabilistic method here to combine all evaluators' estimation towards a system's components and integration points. Based on the probabilistic form of TRLs and IRLs, a Monte-Carlo simulation methodology is followed herein to assess the maturity status (SRL) of a system. An illustrative example is examined to show how to employ the proposed methodology. The paper concludes with the discussion of the gained value of the new methodology as well as its limitation.

## Introduction

In the 1990's, the National Aeronautics and Space Administration (NASA) instituted a nine-level metric to systematically assess the maturity of technologies that were being developed. This metric, called Technology Readiness Level (TRL), described below in Table 1, enabled the consistent comparison of different types of technologies with regard to their maturity (Mankins 1995).

Given the pragmatic benefits of this concept, other government agencies such as the Department of Defense(DoD 2008), Department of Energy and the National Air and Space Intelligence Center have adopted the TRL to measure the maturity of technologies. The TRL metric provides the government agencies and their contractors a common reference point to describe the readiness of technologies under development. However, it was never intended to measure the integration of the technologies (Sadin, Povinelli, and Rosen 1989). Consequently, TRL can not address:

a) A complete representation of the (difficulty of) integration of the subject technology or subsystems into an operational system (Dowling and Pardoe 2005; Mankins 2002; Valerdi and Kohl 2004),
b) The uncertainty that may be expected in moving through the maturation of TRL (Cundiff 2003; Dowling and Pardoe 2005; Mankins 2002; Smith 2005), and

c) Comparative analysis techniques for alternative TRLs (Cundiff 2003; Dowling and Pardoe 2005; Mankins 2002; Smith 2005).

Table 1: Technology Readiness Levels

| TRL | Definition |
|---|---|
| **9** | Actual System Proven Through Successful Mission Operations |
| **8** | Actual System Completed and Qualified Through Test and Demonstration |
| **7** | System Prototype Demonstrations in Relevant Environment |
| **6** | System/Subsystem Model or Prototype Demonstration in Relevant Environment |
| **5** | Component and/or Breadboard Validation in Relevant Environment |
| **4** | Component and/or Breadboard Validation in Laboratory Environment |
| **3** | Analytical and Experimental Critical Function and/or Characteristic Proof-of-Concept |
| **2** | Technology Concept and/or Application Formulated |
| **1** | Basic Principals Observed and Reported |

Therefore, the issue of measuring the maturity of the integration elements needs to be addressed. The very first attempt to address this was done by Mankins (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. Although the study brought to the forefront the difficulty of progressing through the TRL index and choosing between competing alternative technologies, it did not adequately address the integration aspects of systems development. This was addressed by the Ministry of Defence of the United Kingdom when it formulated an Integration Maturity Level as part of its Technology Insertion Metric (Dowling and Pardoe 2005).

Building upon these efforts, Gove (Gove, Sauser, and Ramirez-Marquez 2007) and Gove, et. al. (Gove, Sauser, and Ramirez-Marquez 2007) performed a thorough 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). It has since evolved into the nine-level concept described in Table 2.

IRL is a systematic measurement of the interfacing of compatible interactions for various technologies and the consistent comparison of the maturity between integration points. The introduction of IRL to the assessment process not only provides a check as to where the technology is on an integration readiness scale but also presents a direction for improving integration among technologies. Just as TRL has been used to assess the risk associated with developing technologies, IRL is designed to assess the risk associated with integrating these technologies.

Table 2: Integration Readiness Levels

| IRL | Definition |
|---|---|
| **9** | Integration is **Mission Proven** through successful mission operations. |
| **8** | Actual integration completed and **Mission Qualified** through test and demonstration, in the system environment. |
| **7** | The integration of technologies has been **Verified and Validated** with sufficient detail to be actionable. |
| **6** | The integrating technologies can **Accept, Translate, and Structure Information** for its intended application. |
| **5** | There is sufficient **Control** between technologies necessary to establish, manage, and terminate the integration. |
| **4** | There is sufficient detail in the **Quality and Assurance** of the integration between technologies. |
| **3** | There is **Compatibility** (i.e. common language) between technologies to orderly and efficiently integrate and interact. |
| **2** | There is some level of specificity to characterize the **Interaction** (i.e. ability to influence) between technologies through their interface. |
| **1** | An **Interface** between technologies has been identified with sufficient detail to allow characterization of the relationship. |

Now that both the technologies and integration elements can be assessed and mapped along an objective numerical scale, another challenge emerges which is to develop a metric that can assess the maturity of the entire system that is under development. Sauser, et al. (Sauser, Ramirez-Marquez, Henry et al. 2008) were able to demonstrate how using a normalized matrix of pair-wise comparisons of TRLs and IRLs for any system under development can yield a measure of system maturity, called Systems Readiness Level (SRL). The SRL metric can be used to determine the maturity of a system and its status within a developmental life cycle. Table 3 presents the definitions of the various levels of the SRL and a representation of how the SRL index correlates to a systems engineering life cycle.

Table 3: System Readiness Levels

| SRL | Acquisition Phase | Definitions |
|---|---|---|
| 0.90 to 1.00 | **Operations & Support** | Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle. |
| 0.70 to 0.89 | **Production** | Achieve operational capability that satisfies mission needs. |
| 0.60 to 0.79 | **System Development & Demonstration** | Develop system capability or (increments thereof); reduce integration and manufacturing risk; ensure operational supportability; reduce logistics footprint; implement human systems integration; design for production; ensure affordability and protection of critical program information; and demonstrate system integration, interoperability, safety and utility. |
| 0.40 to 0.59 | **Technology Development** | Reduce technology risks and determine appropriate set of technologies to integrate into a full system. |
| 0.10 to 0.39 | **Concept Refinement** | Refine initial concept; Develop system/technology strategy. |

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

Mathematically, the procedure of calculating the composite SRL is as follow (assuming n technologies within the system):

a) Normalize the [1, 9] scale Raw TRLs and IRLs into (0,1) scale TRLs and IRLs, denote them by matrices:

$$(1)\quad [TRL]_{n\times 1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \cdots \\ TRL_n \end{bmatrix} \xrightarrow{normalize} \begin{bmatrix} TRL_1 \\ TRL_2 \\ \cdots \\ TRL_n \end{bmatrix};$$

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

Where IRLij=IRLji; when no integration between two technologies, an Raw IRL value of 0 is assigned and for integration with technology itself, an Raw IRL value of 9 is used, that is Raw IRLii=9.

b) Component SRL matrix is the product of TRL and IRL matrices:

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

$$(3)\quad \begin{bmatrix} SRL_1 \\ SRL_2 \\ \ldots \\ SRL_n \end{bmatrix} = \begin{bmatrix} 1/m_1 & 0 & \ldots & 0 \\ 0 & 1/m_2 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & \ldots & 1/m_n \end{bmatrix} \times \begin{bmatrix} IRL_{11} & IRL_{12} & \ldots & IRL_{1n} \\ IRL_{21} & IRL_{22} & \ldots & IRL_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ IRL_{n1} & IRL_{n2} & \ldots & IRL_{nn} \end{bmatrix} \times \begin{bmatrix} TRL_1 \\ TRL_2 \\ \cdots \\ TRL_n \end{bmatrix}$$

$$= \begin{bmatrix} (IRL_{11}TRL_1 + IRL_{12}TRL_2 + \ldots + IRL_{1n}TRL_n)/m_1 \\ (IRL_{21}TRL_1 + IRL_{22}TRL_2 + \ldots + IRL_{2n}TRL_n)/m_2 \\ \ldots \\ (IRL_{n1}TRL_1 + IRL_{n2}TRL_2 + \ldots + IRL_{nn}TRL_n)/m_n \end{bmatrix}$$

Where $m_i$ is the number of integrations of technology i with itself and all other technologies, and [Norm] is to normalize the $SRL_i$ from (0, $m_i$) scale to (0, 1) scale for consistency, thus [Norm]=diag[$1/m_1$, $1/m_2$, …, $1/m_n$].

c) Composite SRL is the average of all component SRLs:

$$(4)\quad SRL = \frac{SRL_1 + SRL_2 + \ldots + SRL_n}{n} = \frac{\sum_{i=1}^{n} SRL_i}{n}.$$

To illustrate the SRL calculation, the following example will use a simple system of three technologies and two integrations (see Fig. 1) to show the steps involved in calculating the SRL value.

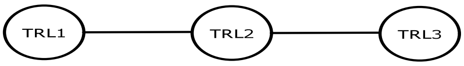

Figure 1: System with three technologies (1, 2 & 3) and two integrations

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

$$[TRL] = \begin{bmatrix} TRL_1 \\ TRL_2 \\ TRL_3 \end{bmatrix} = \begin{bmatrix} 9 \\ 6 \\ 6 \end{bmatrix} \xrightarrow{normalize} \begin{bmatrix} 1.00 \\ 0.67 \\ 0.67 \end{bmatrix}$$

$$[IRL] = \begin{bmatrix} IRL_{11} & IRL_{12} & IRL_{13} \\ IRL_{21} & IRL_{22} & IRL_{23} \\ IRL_{31} & IRL_{32} & IRL_{33} \end{bmatrix} = \begin{bmatrix} 9 & 1 & 0 \\ 1 & 9 & 7 \\ 0 & 7 & 9 \end{bmatrix} \xrightarrow{normalize} \begin{bmatrix} 1.00 & 0.11 & 0.00 \\ 0.11 & 1.00 & 0.78 \\ 0.00 & 0.78 & 1.00 \end{bmatrix}$$

Note that there is no integration between technologies 1 and 3 in this system and hence the integration IRL13=IRL31=0 and the IRL for self-integrations is 9 as per definition. Since here [Norm]=diag[1/2, 1/3, 1/2], the SRL would be:

$$[SRL] = [Norm] \times [IRL] \times [TRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ SRL_3 \end{bmatrix} = \begin{bmatrix} 0.54 \\ 0.43 \\ 0.60 \end{bmatrix}$$

$$SRL = \frac{SRL_1 + SRL_2 + SRL_3}{3} = \frac{0.54 + 0.43 + 0.60}{3}$$

$$SRL = 0.52$$

Despite the utility of calculating a SRL, without an articulated correlation to qualitative systems engineering practices, it becomes difficult to determine the added value in understanding its implication on the developmental life cycle. Sauser et al. (Sauser, Ramirez-Marquez, Henry et al. 2008) were able to use documented qualitative data to calculate the SRL for four systems in development and correlate how the SRL of these systems can be described using any of four standard systems engineering life cycles (i.e. Typical High-Technology System, ISO 15288, DoD, and NASA). These cases represented systems development successes and failures, levels of abstraction, and views in retrospect. Finally, the authors of this paper have subsequently performed further verification and validation of this approach to other cases in conjunction with system developers from DoD, Lockheed-Martin, NASA, and Northrop Grumman. Thus, to provide a subjective assessment of system maturity, the SRL approach is used.

So far, all the papers (Ramirez-Marquez and Sauser 2008; Sauser, Ramirez-Marquez, Henry et al. 2008; Sauser et al. 2007; Sauser, Ramirez-Marquez, Magnaye et al. 2008; Sauser, Verma, and Ramirez-Marquez 2006) related to SRL estimation applied the assumption that all the inputs (TRL's & IRL's) of a system assume deterministic values. While in this way it was relatively easy and somewhat adequate to communicate the status of the technologies, we contend that it does not match the dynamic and probabilistic environment in which the values are determined. Just as Ramirez-Marquez and Sauser (Ramirez-Marquez and Sauser 2008) mentioned in their paper, it is more rational to assume that the evaluation of TRL's and IRL's follow a probabilistic form. Moreover, the methods proposed in those papers (Ramirez-Marquez and Sauser 2008; Sauser, Ramirez-Marquez, Henry et al. 2008; Sauser et al. 2007; Sauser, Ramirez-Marquez, Magnaye et al. 2008; Sauser, Verma, and Ramirez-Marquez 2006) just provided us a unique value for the SRL of the system in consideration. Though that may be enough for brief analysis, in order to get the information on risk which is associated with human subjectivity, there should also be a formal requirement to place a confidence level on information and to make a decision (Redmill 2002).

To capture these insights, we apply a basic assumption - that the evaluation of the TRL follows a probabilistic form. We propose to incorporate the complete information that the stakeholders provided by using the relative frequency of the TRL values generated as a probability distribution to combine every evaluator's judgment of the readiness of the technology. That is, the dispersion in the TRL and IRL estimates can be represented in the values that are calculated. Information that shows the degree of precision that accompanies an SRL estimate can be very useful to a decision maker when determining, among others, the risk-return trade offs. Based on these assumptions, a Monte-Carlo simulation approach is applied to yield an estimation of the SRL which matches reality better. Then this approach will be implemented in a case example to demonstrate its capabilities for risk analysis during systems development.

## Methodology For SRL Confidence Interval Estimation

Prescriptive techniques allow people to make better decisions by using normative models, but with knowledge of the limitations and descriptive realities of human judgment (Smith and Winterfeldt 2004). In project and engineering management one of the prescriptive tools used are soft metrics which are measured through subjective judgment and are relatively easy to derive, but require a complementary rationale that explains the assessment (Dowling and Pardoe 2005). Currently, the most common methods for determining a TRL are done by: (1) Individual Expert: an expert in the technology or TRLs assesses its state of maturity; (2) Group: the maturity is determined through a discussion among the technology's stakeholders; and (3) Assessment Tool: the use of guidance documentation or a software tool that directs the maturity assessment (e.g. the DoD Technology Readiness Assessment Deskbook; the AFRL TRL calculator). However, these techniques of estimation are human-intensive and are therefore subjective. Whenever the assessment is made by human beings, there is subjectivity included in the assessment result. Wherever the subjectivity exists, there is risk associated. Thus there are also such decision situations, where the decision maker has to try to eliminate subjectivity from decisions as far as possible (Benedikt 1993).

To capture this insight, we propose a new probabilistic approach here to combine all evaluators' estimation, and a Monte-Carlo simulation approach for system SRL estimation. There are mainly three steps to apply the new methodology, which is shown below.

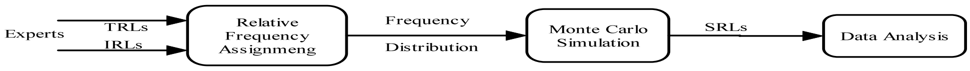

Figure 2: Steps of the Methodology

Step 1: Suppose there are s evaluators to examine a system with n technologies. Each TRL and potential IRL between any two technologies may be estimated with several readiness level numbers which fall in the range of [0, 9]. Let $f_{i,k}$ indicates the number of evaluators setting a readiness level of k to technology i, and $f_{ij,k}$ indicates the number of evaluators setting a readiness level of k to integration between technology i and j. To get the frequency distribution, we calculate the relative frequency for each TRL/IRL. That is:

$$p_{i,k} = f_{i,k} / s, \quad p_{ij,k} = f_{ij,k} / s \qquad \text{Where } i,j=1,\ldots,n;\ k=0,1,\ldots,9.$$

Step 2: Monte-Carlo simulation is a computational algorithm that relies on repeated random sampling to compute its results. Mainly there are three steps to implement Monte-Carlo simulation:

1. Define a domain of possible inputs.
2. Generate inputs randomly from the domain, and perform a deterministic computation on them.
3. Aggregate the results of the individual computations into the final result.

Accepting the TRL/IRL frequency distributions as input data, random numbers are then generated to randomly select readiness level for TRL/IRL within the domain. With these attained random inputs, in one iteration, the system's composite SRL are calculated by the deterministic formula described mentioned before. This process continues to simulate the SRL calculation until the predetermined number of iterations is reached. Moreover, in each iteration the simulation results of component SRLs and system composite SRL are updated in data sets $D_1$, $D_2$, …, $D_n$, and D, respectively. These data sets are used for further system analysis.

Step 3: Using the data set from step 2, we can get the probability density function plot and cumulative density function plot for the system composite SRL. Instead of providing a deterministic SRL without any variation information, the SRL probability distribution can provide project managers with more certainty about the current maturity status of the system in question and more flexibility for further decision making.

## Illustrative Case Study

Here, we use an example, which was also examined in(Sauser, Ramirez-Marquez, Magnaye et al. 2008), to demonstrate how to apply the methodology. The system is currently under development and will be used with a family of surface ships for the U.S. Navy. The system architecture analyzed (see Figure 1) represents an end-to-end integration of command and control capabilities with a variety of unmanned vehicles and intelligence, surveillance, and reconnaissance sensor packages. These elements are capable of autonomous operations and include both off-the-shelf equipment and cutting edge new development networked seamlessly together to enhance effectiveness and efficiency.

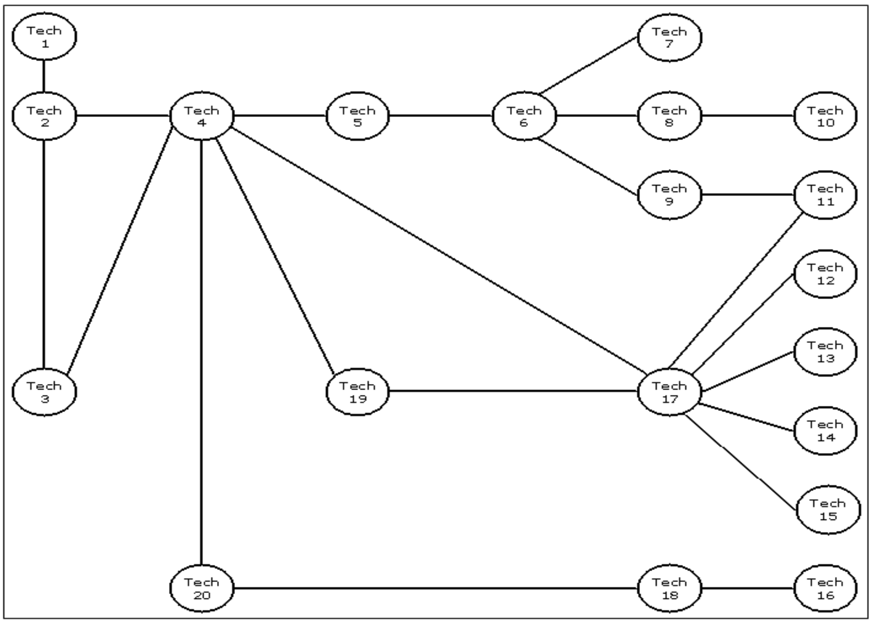

Figure 3: System Concept Diagram of Example 2

Within the system, there are 20 technologies with 22 integrations. Table 4 assumes the estimation for TRLs and IRLs from 100 evaluators.

Table 4: TRL's & IRL's Estimate

| Technology | TRL | | | Frequency (fi,k) | | | Total | Integration | IRL | | | Frequency (fij,k) | | | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 9 | | | 100 | | | 100 | 1,2 | 9 | | | 100 | | | 100 |
| 2 | 9 | | | 100 | | | 100 | 2,3 | 8 | 9 | | 20 | 80 | | 100 |
| 3 | 9 | | | 100 | | | 100 | 2,4 | 7 | 8 | 9 | 5 | 80 | 15 | 100 |
| 4 | 6 | 7 | 8 | 15 | 80 | 5 | 100 | 3,4 | 6 | 7 | 8 | 10 | 80 | 10 | 100 |
| 5 | 5 | 6 | 7 | 25 | 70 | 5 | 100 | 4,5 | 5 | 6 | 7 | 20 | 70 | 10 | 100 |
| 6 | 9 | | | 100 | | | 100 | 4,17 | 4 | 5 | 6 | 15 | 60 | 25 | 100 |
| 7 | 9 | | | 100 | | | 100 | 4,19 | 4 | 5 | 6 | 35 | 60 | 5 | 100 |
| 8 | 6 | 7 | 8 | 10 | 70 | 20 | 100 | 4,20 | 5 | 6 | 7 | 20 | 70 | 10 | 100 |
| 9 | 5 | 6 | 7 | 40 | 50 | 10 | 100 | 5,6 | 6 | 7 | 8 | 30 | 60 | 10 | 100 |
| 10 | 9 | | | 100 | | | 100 | 6,7 | 8 | 9 | | 80 | 20 | | 100 |
| 11 | 8 | 9 | | 20 | 80 | | 100 | 6,8 | 7 | 8 | | 30 | 70 | | 100 |
| 12 | 7 | 8 | 9 | 25 | 70 | 5 | 100 | 6,9 | 6 | 7 | 8 | 5 | 70 | 25 | 100 |
| 13 | 6 | 7 | 8 | 25 | 70 | 5 | 100 | 8,10 | 5 | 6 | 7 | 30 | 50 | 20 | 100 |
| 14 | 5 | 6 | 7 | 10 | 70 | 20 | 100 | 9,11 | 4 | 5 | 6 | 80 | 15 | 5 | 100 |
| 15 | 7 | 8 | 9 | 30 | 60 | 10 | 100 | 11,17 | 4 | 5 | 6 | 50 | 40 | 10 | 100 |
| 16 | 6 | 7 | 8 | 50 | 40 | 10 | 100 | 12,17 | 9 | | | 100 | | | 100 |
| 17 | 5 | 6 | 7 | 70 | 25 | 5 | 100 | 13,17 | 9 | | | 100 | | | 100 |
| 18 | 7 | 8 | 9 | 30 | 65 | 5 | 100 | 14,17 | 8 | 9 | | 20 | 80 | | 100 |
| 19 | 9 | | | 100 | | | 100 | 15,17 | 7 | 8 | 9 | 15 | 80 | 5 | 100 |
| 20 | 9 | | | 100 | | | 100 | 16,18 | 7 | 8 | 9 | 25 | 60 | 15 | 100 |
| | | | | | | | | 17,19 | 9 | | | 100 | | | 100 |
| | | | | | | | | 18,20 | 6 | 7 | 8 | 5 | 80 | 15 | 100 |

*Step 1:* In order to get the frequency distribution for each TRL/IRL, divide every frequency number in table 4 by the corresponding total number in the total column. It can also be seen as a frequency normalization process. Because this is the full information about the technologies and integrations of the system, it can therefore be considered as a good representative of the component status and it is suitable to assume them as the input data for further SRL estimation. The frequency distribution of the TRL/IRL is shown in Table 5 below.

Table 5: TRL/IRL Frequency Distribution

| Technology | TRL | Probablity ($p_{i,k}$) | Total | Integration | IRL | Probability ($p_{ij,k}$) | Total |
|---|---|---|---|---|---|---|---|
| 1 | 9 | 1 | 1 | 1,2 | 9 | 1 | 1 |
| 2 | 9 | 1 | 1 | 2,3 | 8 9 | 0.2 0.8 | 1 |
| 3 | 9 | 1 | 1 | 2,4 | 7 8 9 | 0.05 0.8 0.15 | 1 |
| 4 | 6 7 8 | 0.15 0.8 0.05 | 1 | 3,4 | 6 7 8 | 0.1 0.8 0.1 | 1 |
| 5 | 5 6 7 | 0.25 0.7 0.05 | 1 | 4,5 | 5 6 7 | 0.2 0.7 0.1 | 1 |
| 6 | 9 | 1 | 1 | 4,17 | 4 5 6 | 0.15 0.6 0.25 | 1 |
| 7 | 9 | 1 | 1 | 4,19 | 4 5 6 | 0.35 0.6 0.05 | 1 |
| 8 | 6 7 8 | 0.1 0.7 0.2 | 1 | 4,20 | 5 6 7 | 0.2 0.7 0.1 | 1 |
| 9 | 5 6 7 | 0.4 0.5 0.1 | 1 | 5,6 | 6 7 8 | 0.3 0.6 0.1 | 1 |
| 10 | 9 | 1 | 1 | 6,7 | 8 9 | 0.8 0.2 | 1 |
| 11 | 8 9 | 0.2 0.8 | 1 | 6,8 | 7 8 | 0.3 0.7 | 1 |
| 12 | 7 8 9 | 0.25 0.7 0.05 | 1 | 6,9 | 6 7 8 | 0.05 0.7 0.25 | 1 |
| 13 | 6 7 8 | 0.25 0.7 0.05 | 1 | 8,10 | 5 6 7 | 0.3 0.5 0.2 | 1 |
| 14 | 5 6 7 | 0.1 0.7 0.2 | 1 | 9,11 | 4 5 6 | 0.8 0.15 0.05 | 1 |
| 15 | 7 8 9 | 0.3 0.6 0.1 | 1 | 11,17 | 4 5 6 | 0.5 0.4 0.1 | 1 |
| 16 | 6 7 8 | 0.5 0.4 0.1 | 1 | 12,17 | 9 | 1 | 1 |
| 17 | 5 6 7 | 0.7 0.25 0.05 | 1 | 13,17 | 9 | 1 | 1 |
| 18 | 7 8 9 | 0.3 0.65 0.05 | 1 | 14,17 | 8 9 | 0.2 0.8 | 1 |
| 19 | 9 | 1 | 1 | 15,17 | 7 8 9 | 0.15 0.8 0.05 | 1 |
| 20 | 9 | 1 | 1 | 16,18 | 7 8 9 | 0.25 0.6 0.15 | 1 |
|  |  |  |  | 17,19 | 9 | 1 | 1 |
|  |  |  |  | 18,20 | 6 7 8 | 0.05 0.8 0.15 | 1 |

*Step 2:* For system whose concept diagram is shown in Figure 1, its parameters are shown as follows:

Table 6: Example Parameters

| n | L | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_5$ | $m_6$ | $m_7$ | $m_8$ | $m_9$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 20 | 50,000 | 2 | 4 | 3 | 7 | 3 | 5 | 2 | 3 | 3 |
| $m_{10}$ | $m_{11}$ | $m_{12}$ | $m_{13}$ | $m_{14}$ | $m_{15}$ | $m_{16}$ | $m_{17}$ | $m_{18}$ | $m_{19}$ | $m_{20}$ |
| 2 | 3 | 2 | 2 | 2 | 2 | 2 | 8 | 3 | 3 | 3 |

Note: $m_i$ is the number of integrations of technology i with itself and all other technologies

After 50,000 iterations, the simulation results for all component SRLs and system composite SRL are stored in data sets ***$D_1$, $D_2$,…, $D_{20}$ and D***.

*Step 3:* Using the simulation data sets ***$D_1$, $D_2$,…, $D_{20}$ and D,*** we plot the probability density function and cumulative distribution function of the composite SRL, which are shown below:

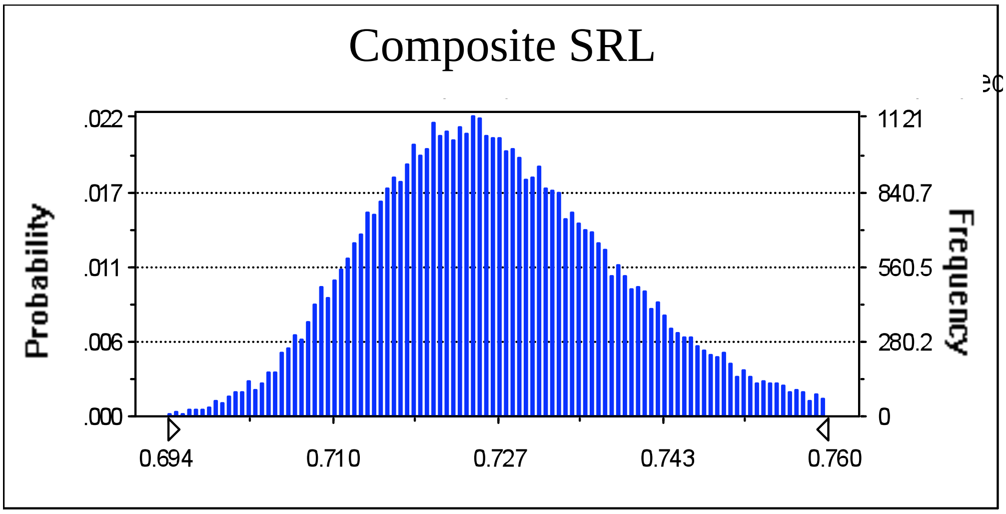

Figure 4: Probability Density Function of System Composite SRL

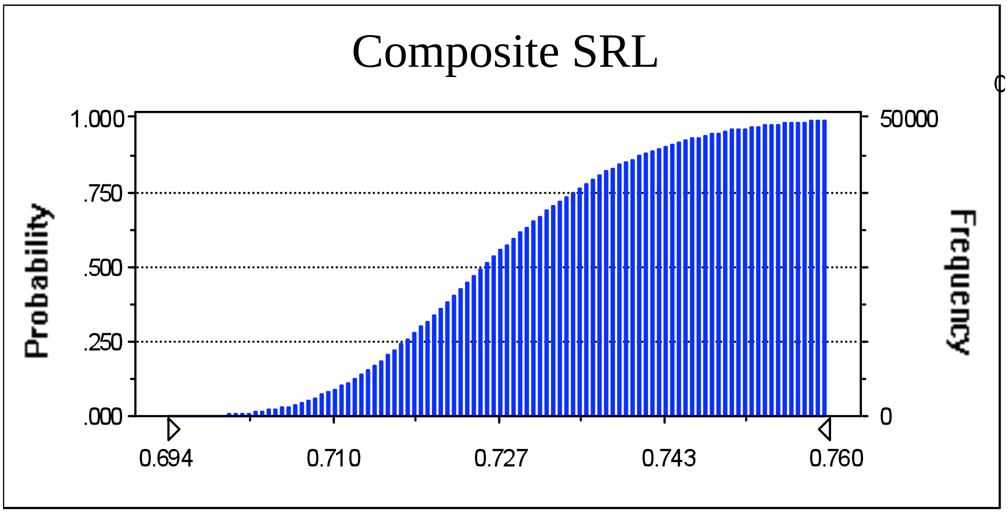

Figure 5: Cumulative Distribution Function of System Composite SRL

Table 7: Statistics from Simulation

| | **SRL** | **SRL$_{1}$** | **SRL$_{2}$** | **SRL$_{3}$** | **SRL$_{4}$** | **SRL$_{5}$** | **SRL$_{6}$** | **SRL$_{7}$** | **SRL$_{8}$** | **SRL$_{9}$** | **SRL$_{10}$** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Mean** | **0.727** | 1.000 | 0.917 | 0.858 | 0.562 | 0.634 | 0.716 | 0.956 | 0.766 | 0.632 | 0.758 |
| **Median** | **0.726** | 1.000 | 0.923 | 0.868 | 0.561 | 0.630 | 0.714 | 0.944 | 0.778 | 0.630 | 0.759 |
| Std | **0.013** | 0.000 | 0.018 | 0.023 | 0.020 | 0.035 | 0.024 | 0.022 | 0.037 | 0.037 | 0.037 |
| 5% | **0.708** | 1 | 0.895 | 0.815 | 0.527 | 0.58 | 0.677 | 0.944 | 0.704 | 0.576 | 0.716 |
| 95% | **0.75** | 1 | 0.944 | 0.897 | 0.594 | 0.691 | 0.758 | 1 | 0.815 | 0.704 | 0.802 |
| | **SRL** | **SRL$_{11}$** | **SRL$_{12}$** | **SRL$_{13}$** | **SRL$_{14}$** | **SRL$_{15}$** | **SRL$_{16}$** | **SRL$_{17}$** | **SRL$_{18}$** | **SRL$_{19}$** | **SRL$_{20}$** |
| **Mean** | **0.727** | 0.527 | 0.730 | 0.675 | 0.629 | 0.694 | 0.745 | 0.697 | 0.765 | 0.637 | 0.642 |
| **Median** | **0.726** | 0.527 | 0.722 | 0.667 | 0.611 | 0.691 | 0.735 | 0.696 | 0.757 | 0.634 | 0.650 |
| Std | **0.013** | 0.029 | 0.043 | 0.043 | 0.045 | 0.046 | 0.054 | 0.021 | 0.037 | 0.027 | 0.026 |
| 5% | **0.708** | 0.477 | 0.667 | 0.611 | 0.556 | 0.636 | 0.679 | 0.662 | 0.716 | 0.605 | 0.593 |
| 95% | **0.75** | 0.58 | 0.833 | 0.778 | 0.722 | 0.79 | 0.84 | 0.733 | 0.823 | 0.687 | 0.683 |

As the estimation of the maturity status of this system is 0.727 with the standard deviation of 0.013 and the 90% percentile interval is [0.708, 0.750], recalling table 3, the results indicate the system is already in the production phase within which the main assignment is to achieve operational capability in order to satisfy mission needs. Different from the unique deterministic way to come up with the system readiness level, here after 50,000 iterations of simulation with all the inputs from all evaluators, we can be considerable confident in our evaluation towards the system in question.

## Conclusion

A System Readiness Level (SRL) index which incorporates both the current Technology Readiness Level (TRL) scale and the concept of an Integration Readiness Level (IRL) has recently been established to assess systems' maturity at the system level. Previous related research calculated the SRL as a deterministic value assuming that TRLs and IRLs are evaluated deterministically. However, this paper proposes a Monte-Carlo simulation methodology for estimating the system readiness level, assuming that TRLs and IRLs are probabilistically distributed and thus combining all evaluators' estimation. With the tool of Monte-Carlo simulation, it is easy here to dynamically identify how the system composite SRL spreads over its range, with which estimators can be much more confident about the maturity status of the system and provide project managers more insights on the risk associated with the system. Although the illustrative example in the paper shows how to apply the method only with the presumed input data, users can tailor the method for their specific application when they have real data.

However, there are some concerns that need further consideration. Since the Monte-Carlo simulation approach depends heavily on the accuracy of the input data, its efficacy will be undermined if the input data can not well represent the real status of the component TRLs/IRLs. If there is enough evidence indicating the hesitation about the quality of the input data, it is necessary to re-evaluate the component TRLs/IRLs. Moreover, data used in the illustrative example were made up in order to show how to use the new methodology, but for a new method to be really useful in reality, real case study must be performed to verify and validate it. Thus, we need to further investigate it with real data from real systems.

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