Application of **System and Integration** ${\color{orange}\textbf{READINESS LEVELS}}$ to Department of Defense **RESEARCH** and **DEVELOPMENT**

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Technology Readiness Level only tells part of the story of system maturation. As component technologies are developed to become part of systems, there are also integration and manufacturing issues to consider. This article improves upon the System and Integration Readiness Level concepts previously developed by B. J. Sauser et al., combines the concepts of Technology, Integration, and Manufacturing Readiness Levels, adapted for use in defense acquisition, into a single metric—System Readiness Level. This metric can then be used as an indicator to identify areas for resource allocation to enable the most efficient path to technology transition and to prevent premature system advancement.

In an ideal world, a component technology would develop concurrently with its interfaces and its ability to be manufactured. In the real world, technologies lead both their interfaces and manufacturing infrastructure. For example, motorcycles were first made with fixed foot-pegs until some rather spectacular, spin-out wrecks occurred, prompting folding foot-pegs. The human-motorcycle interface maturity followed the technical maturity at the expense of safety. Early airplanes were made, one-at-a-time, with bicycle manufacturing equipment. The manufacturing maturity lagged the technology. The competing pitfall in system development is the premature advancement of a technology to the next level of development in advance of its interfaces, such as the current state of the F-35 program. Although the program is in late stage development, interface and component technology issues are still emerging that are preventing full operational capability (Bender, 2015). We can do a better job by minimizing the gap between interface, manufacturing, and technology maturity. Integration and system readiness are not yet implemented in any formal way Department of Defense (DoD)-wide.

This article explains a method to combine Technology Readiness Level (TRL) (See Appendix, Table A-1), Integration Readiness Level (IRL), and Manufacturing Readiness Level (MRL) (See Appendix, Table A-2) into a single metric—System Readiness Level (SRL)—that can provide guidance to decision makers during the technology maturation process. Such guidance can minimize the delays and mishaps likely to occur when interfaces and manufacturing significantly lag their component technologies.

Background

The DoD Research, Development, Test and Evaluation budget is sub-divided into seven separate activities: basic research; applied research; advanced technology development; advanced component development and prototypes; system development and demonstration; research, development, test and evaluation (RDT&E) management support; and operational systems development, i.e., the DoD categories of funding and technology development (Appendix, Table A-3). These seven activities are designated as DoD 6.1 through 6.7. This article incorporates the 6.1 through 6.7 levels of funding and appropriate levels of maturity so that the same metric can be used throughout the acquisition life cycle. Verbal definitions of TRL, MRL, IRL, and SRL are included at the end of the article.

Sauser, Ramirez-Marquez, and Devanandham, and Dimarzio (2007), and Sauser, Ramirez-Marquez, Magnaye, and Tan (2008a) furthered the concepts of TRL to include IRL and SRL (Sauser, Forbes, Long, & McGrory, 2009; Sauser, Gove, Forbes, & Ramirez-Marquez, 2010). These approaches emphasize that the interfaces between subsystems are every bit as important as the subsystems themselves, and that no system can be deemed ready for deployment based on the component technologies alone.

Method

Sauser's basic approach is to imagine a system composed of component technologies from 1 to n, each with a TRL as shown in equation (1) and Figure 1.

$$TRL = trl_i = \{trl_1\, trl_2\, \cdots\, trl_n\}$$

(1)

Mathematical Note. A list of symbols or numbers in braces represents a vector. A subscripted symbol indicates one element out of a vector. A number without subscripts indicates the whole vector quantity. Lower case is used for normalized quantities.

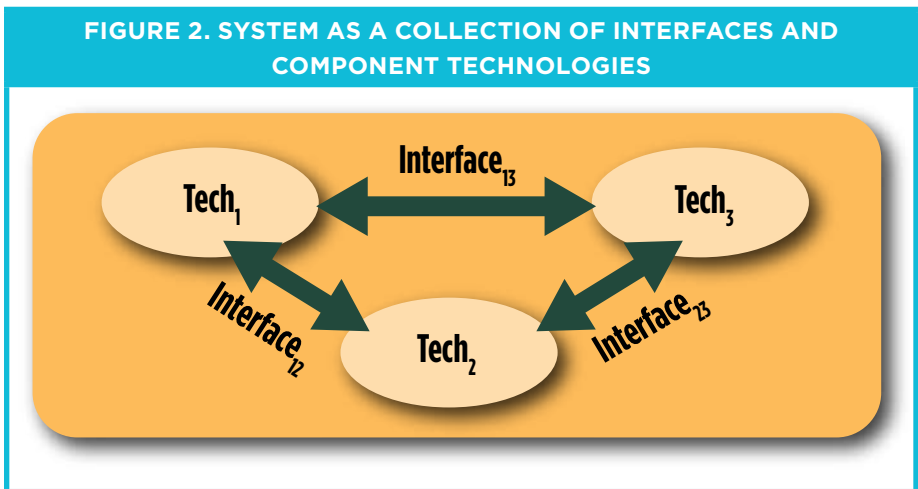**FIGURE 1. A SYSTEM AS A COLLECTION OF COMPONENT TECHNOLOGIES**
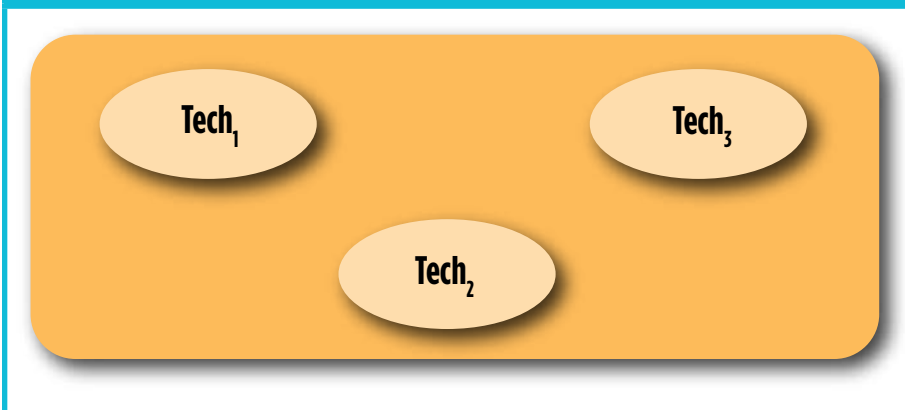
Note. (Sauser, 2008)

For example, a motorcycle can be viewed as an engine, power train, exhaust, electrical system, cooling system, saddle, suspension, wheels, gauges, steering, headlamp, etc.

Each component technology has a potential interface with each other component and with the external environment, including the possibility of an interface going both ways, as shown in equation (2). For simplicity, Figure 2 shows the interfaces with double arrows, as if $irl_{12} = irl_{21}$, which need not be the case. IRL must be expressed as a two-dimensional matrix rather than a one-dimensional vector. The vector is generally square—with the same number of rows and columns. The diagonal of the matrix is not used since a technology always works with itself.

$$IRL = irl_{ij} = \left\{ \begin{array}{ccccc} x & irl_{12} & irl_{13} & \cdots & irl_{1n} \\ irl_{21} & x & irl_{21} & \cdots & irl_{2n} \\ irl_{n1} & irl_{n1} & irl_{n3} & \cdots & irl_{nn} \end{array} \right\}$$

(2)

FIGURE 2. SYSTEM AS A COLLECTION OF INTERFACES AND COMPONENT TECHNOLOGIES

In the Sauser approach, The IRL matrix and the TRL vector are multiplied together as a vector product (U.S. Navy, 2009, p. 35) to form an SRL vector that can be averaged for an overall SRL (Sauser, Verma, Ramirez-Marequez, Gove, 2006, p. A-12; Sauser et al., 2007, p. 681; U.S. Navy, 2009, p. 33). Note that this paper shows matrix notation in both reduced tensor notation and matrix notation as a convenience for a multidisciplinary audience. SRL_j, $[SRL]$ and $\overrightarrow{SRL}$ all refer to the same vector entity and all versions of equation

(3) show the same tensor/matrix operation in different notation. Equation (4) shows the Sauser formula for SRL. Computational and practical examples of all formulas will be shown in the examples section.

$$SRL_j = IRL_{ij}\, TRL^i = IRL1_j\, TRL^1 + IRL_{2j}\, TRL^2 +\ \ + = IRL_{nj}\, TRL^n$$
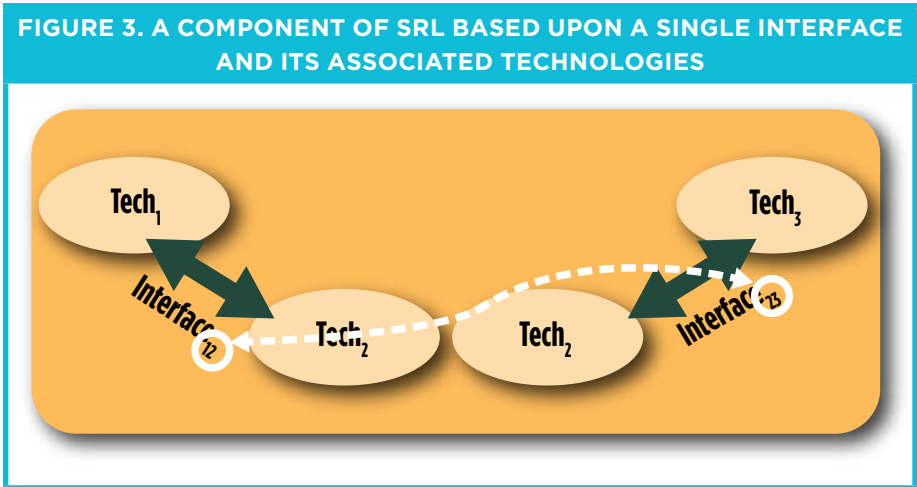
(3a)

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ ... \\ SRL_3 \end{bmatrix} = \begin{bmatrix} IRL_{11}\ TRL_1 + IRL_{12}\ TRL_2 + \cdots\ + IRL_{1n}\ TRL_n \\ IRL_{21}\ TRL_1 + IRL_{22}\ TRL_2 + \cdots\ + IRL_{2n}\ TRL_n \\ ... \\ IRL_{n1}\ TRL_1 + IRL_{n2}\ TRL_2 + \cdots\ + IRL_{nn}\ TRL_n \end{bmatrix}$$

(3b)

$$\overrightarrow{SRL} = \left\{ \begin{array}{ccccc} irl_{11} & irl_{12} & irl_{13} & \cdots & irl_{1n} \\ irl_{12} & irl_{22} & irl_{21} & \cdots & irl_{2n} \\ irl_{13} & irl_{21} & irl_{33} & \cdots & irl_{3n} \end{array} \right\} \left\{ \begin{array}{c} trl_1 \\ trl_2 \\ trl_3 \end{array} \right\}$$
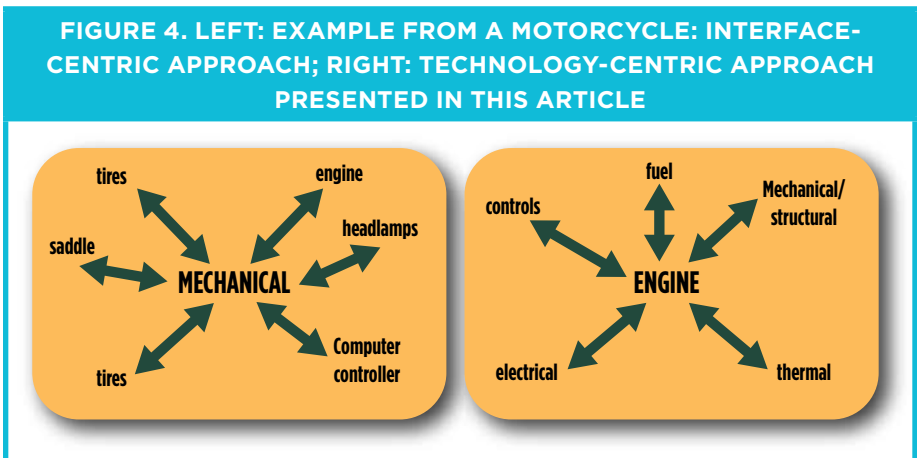
(3c)

$$SRL = \frac{1}{N} \sum_{j=1\,to\,N} srl_j$$

(4)

As shown in equations (3a) and (3b), the Sauser mathematics views a component of SRL (SRL_i) as being based upon a single interface type and its associated technologies; the SRL_1 component includes TRL_1, TRL_2, etc., and all of the IRL_{1n} rather than a technology-centric approach that included TRL_1 with all its interfaces. The interface-centric approach is graphically shown in Figure 3 and contrasted with a technology-centric approach in Figure 4 using a motorcycle. The mechanical component of SRL (SRL_mechanical) in the Sauser approach for a motorcycle would be based upon the mechanical-engine, mechanical-headlamps, mechanical-saddle, mechanical-tires, etc., interfaces. The interface-centric approach has some serious limitations as will be covered in the next sections.

FIGURE 3. A COMPONENT OF SRL BASED UPON A SINGLE INTERFACE AND ITS ASSOCIATED TECHNOLOGIES

Note. (Sauser et al., 2007)

FIGURE 4. LEFT: EXAMPLE FROM A MOTORCYCLE: INTERFACE-CENTRIC APPROACH; RIGHT: TECHNOLOGY-CENTRIC APPROACH PRESENTED IN THIS ARTICLE

Note. Left: (Sauser, 2008). Right: Ross, S. (2016). Application of System and Integration Readiness Levels to Department of Defense Research and Development. *Defense Acquisition Research Journal, 23*(3), In Print.

The average of the SRL vector, equation (4), describes how mature the system is. The Sauser approach may make sense for a single mission or project, such as the deployment of a new software system. However, it has some serious drawbacks for use in research and development where planners need to decide what technologies to develop for the eventual deployment of a new platform, weapon, or system. First, SRL, as defined in the U.S. Navy's *Littoral Combat Ship Mission Module Program System Maturity Assessment Guide* (2009), is *interface*-centric as opposed to *component*-centric. The Sauser definition shows each interface with its associated technologies

rather than each technology with its associated interfaces. Second, SRL as defined by Sauser, has no clear meaning assigned to a given numerical value. In one presentation (Sauser, Ramirez-Marquez, Magnaye, & Tan, 2008b), SRL is defined along a value from 0 to 1 with five unequal intermediate levels and no verbal definitions akin to those for TRL, IRL, and MRL. This gives SRL a different kind of scale than IRL and TRL, which are clearly defined such that 1 is a concept and 9 is full deployment. Third, the Sauser-defined SRL only has meaning at the full system level. The interface-centric components of the SRL vector give no guidance to component developers. Finally, the definitions of IRL tend to be information technology (IT)-centric, emphasizing control and information. IRL needs to be applicable to a wide variety of interfaces, including mechanical, thermal, electrical, structural, and control interfaces as well as logistics, policy, and other '-ility' and mission interfaces.

Characteristics of a Useful System Readiness Level Metric

A useful metric will be defined so as to give a clear indication for planning resource allocation. SRL and IRL, as metrics, can be useful if they are defined correctly. The author proposes the following criteria for a useful SRL and IRL metric.

1. IRL definitions should be applicable to a wide variety of technologies.

2. SRL should be defined such that SRL=1 is a concept and SRL=9 is a mature, deployed system on the same basic scale as TRL, MRL, and IRL.

3. SRL should equal TRL when the interfaces are developed concurrently with the components, and should be less than TRL when interfaces are less mature than the components. This will give planners a clear metric that lets them know that it is time to transition funding into more interface-centric development or to proceed with component technology maturation.

4. SRL should be *technology*- or *component*-centric, not *interface*-centric. This makes it clear when a particular subcomponent is not able to progress further toward implementation due to an interface or manufacturing issue.

5. SRL should include MRL, TRL, and IRL.

6. SRL should be applicable to a wide variety of technical maturities (see Appendix, Table A-3), including basic research (6.1 funding); applied research (6.2 funding); advanced technology development (6.3 funding); advanced component development and prototypes (6.4 funding); system development and demonstration (6.5 funding); and operational systems development (6.7 funding), i.e., the DoD categories of funding and technology development. Note that 6.6 funding is not included because it is for management activities and not tied to a level of technical maturity.

7. SRL must be defined in such a way as to avoid maturity in one component overshadowing immaturity in another (Kujawski, 2010) and giving the illusion that the system is ready to progress. This implies that SRL should never be able to be greater than TRL at either the system or component level.

Proposed System Readiness Level Metric

The author proposes that a more useful way to arrange MRL, TRL, and IRL is as a series of normalized dot products, rather than vector products (Sauser et al., 2008a, p. 47). This changes the view of the components of SRL from being interface-centric to being technology-centric, as shown in the contrast between Figure 3 and Figure 5, and between the right and left sides of Figure 4. The SRL components are equal to the product of the normalized MRL, the TRL, and the mean of the normalized IRL, as shown in Table 1. In the notation that follows, upper case is reserved for standard (i.e., verbal) definitions and lower case is for normalized quantities. Note that the word 'system' in this article refers to a generic system—anything that can be usefully viewed as being composed of parts, rather than specifically as a deployed military asset. Likewise, the term 'component' refers to the parts that make up a larger grouping rather than exclusively as a line-replaceable item with a specific part number. The term interface should be viewed in the broad sense of the word to also include the external environment—the 'ilities' (availability, maintainability, vulnerability, reliability, supportability, etc.) and the DOTmLPF-P (Doctrine, Organization, Training, materiel, Leadership and Education, Personnel, Facilities-Policy).

FIGURE 5. A COMPONENT OF SRL BASED UPON A SINGLE TECHNOLOGY AND ITS INTERFACES
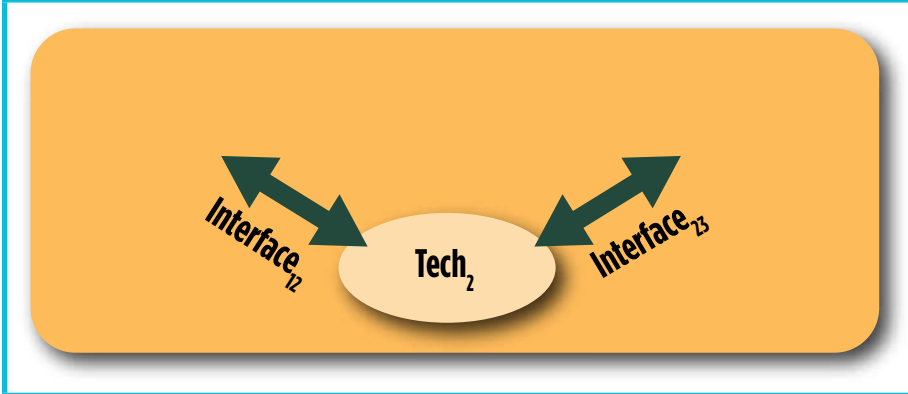
Note. Ross, S., (2016). Application of System and Integration Readiness Levels to Department of Defense Research and Development. *Defense Acquisition Research Journal, 23*(3), In Print.

TABLE 1. NORMALIZED INTEGRATION READINESS LEVEL DEFINITIONS

IRL =	Integration readiness level scalar
IRL_{jk} =	IRL for the interface between technology j and technology k
irl_{jk} =	normalized IRL for interface between technology j and technology k
irl_{jj} =	1, the interface always works with itself
irl_{jk} =	irl_{kj}, the interface works both ways. It may be useful for some systems to break the IRL apart into two components. For purposes of this article, the author assumes that if the motor-fuel interface works, so does the fuel-motor interface.
irl =	IRL/i*

Research level	6.1	6.2	6.3	6.4	6.5	6.6	6.7
i*	1	2	3	5	6	7	9

$$\overline{irl}_i = mean[irl_{ij}]\frac{1}{n}\sum_{j=1}^{n} irl_{ij}$$

To have SRL equal to TRL when IRL and MRL are at commensurate levels of development requires normalized versions of IRL and MRL scaled to the level of research. Basic research (6.1 funding) should have a goal of an IRL of 1 (Interface identification) and MRL of 2 (Manufacturing concepts

identified), so that the normalized *mrl* and *irl* equal 1 when the appropriate levels of IRL and MRL are reached. Likewise, system development and demonstration (6.5 funding) should have as its goal an IRL of 6 (interface control) and an MRL of 6 (prototype in a production-relevant environment) so the normalized *mrl* and *irl* equal 1 when the appropriate levels are reached. The signal to proceed to the next step in system development occurs when SRL equals TRL, indicating that the interfaces and manufacturing base are at a commensurate level of development with the component technologies. The nomenclature and definitions for normalized IRL are shown in Table 1. The normalization factors are chosen to be consistent with the funding categories listed in the DoD Research, Development, Test and Evaluation (RDT&E) budget (Appendix, Table A-3). Different communities may have differing levels of MRL, TRL, and IRL goals vs. acquisition stage so that the normalization factors are intended as starting suggestions. It would also be viable to have normalization factors based on the DoD 5000.02 Model 1 (DoD, 2015).

The normalized IRLs associated with a particular technology need to be averaged to come up with a representative number indicating how well that particular technology relates to the other subsystems or technologies in the system. The $\overline{irl}_i$ accomplish this. Note that the normalization factors 'reset' the metric at each level of maturity, which reduces the possibility of one very mature component masking a less mature one in the metric. MRL normalizations and definitions are shown in Table 2. Note that the normalized MRL (*mrl*) does not replace the existing MRL, but is an intermediate step needed for SRL calculation as is the normalized IRL (*irl*).

TABLE 2. NORMALIZED MANUFACTURING READINESS LEVEL DEFINITIONS						
MRL_j =	MRL for technology j					
mrl_j =	normalized MRL for technology j					
mrl_j =	MRL_j/m^*					
Research level	6.1	6.2	6.3	6.4	6.5	6.6	6.7
m*	2	3	4	5	6	8	10

The SRL metric is formed by multiplying the normalized MRL, the TRL, and the mean of the normalized IRL in a scalar contraction (dot product) such that each component SRL_i has a value from 1 to TRL as does the scalar SRL. System readiness definitions and nomenclature are shown in Table 3.

| TABLE 3. SYSTEM READINESS LEVEL DEFINITIONS AND NOMENCLATURE	
SRL =	System readiness level scalar, the mean of the system readiness levels for all component technologies
SRL_j =	System readiness level for component j

$$SRL_i = mrl_i\, TRL_i\, \overline{irl}_i$$

$$SRL = mean[\{mrl_1\, mrl_2\, ...\, mrl_n\}.\{TRL_1\, TRL_2\, ...\, TRL_n\}.\{\overline{irl}_1\, \overline{irl}_2\, ...\, \overline{irl}_n\}]$$

Numerical Examples

For simplicity and clarity, this article shows three numerical-only examples using a hypothetical system with three technologies, as shown in Figure 6.

FIGURE 6. EXAMPLE SYSTEM WITH THREE COMPONENT TECHNOLOGIES
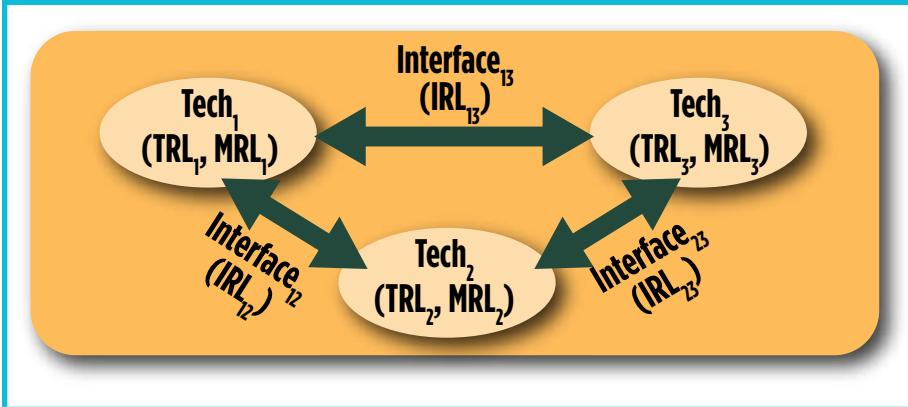
Each technology has an associated TRL and MRL. Each Interface has an associated IRL. Notationally, this will be of the form shown in equations (6), (7), and (8).

$$TRL_i = \{TRL_1, TRL_2, TRL_3\}$$

(6)

$$MRL_i = \{MRL_1, MRL_2, MRL_3\}.$$

(7)

$$\text{IRL}_{ij} = \left\{ \begin{array}{ccc} X & IRL_{12} & IRL_{13} \\ X & X & IRL_{23} \\ X & X & X \end{array} \right\}$$

(8)

Early Technology with Adequate Interfaces

The author assumes a simple, three-component system, with components 1, 2, and 3 funded at the 6.2—applied research level—using the following values for MRL, TRL, and IRL shown in equations (9), (10), (11), and (12).

$$\text{MRL}_i = \{2,3,3\}$$

(9)

$$\text{TRL}_i = \{3,2,4\}$$

(10)

$$\overline{\text{TRL}} = mean[3,2,4] = 3$$

(11)

$$\text{IRL}_{ij} = \left\{ \begin{array}{ccc} X & IRL_{12} & IRL_{13} \; = 2 \\ X & X & IRL_{23} \; = 2 \\ X & X & X \end{array} \right\}$$

(12)

The first step is to calculate the normalized *mrl* and *irl* using the equations from Tables 1 and 2. Because this is 6.2 funded, the m^* normalization factor is 3 from Table 2, indicating that we expect 6.2 funded technologies to be at an MRL of 3 before progressing. Likewise, the i^* normalization factor is 2 from Table 1. Normalized values are shown in equations (13), (14), and (15).

$$\text{mrl}_i = \text{MRL}_i / m^* = \{2,3,3\}/3 = \{0.66,1,1\}$$

(13)

$$\text{irl}_{ij} = \text{IRL}_{ij} / 2 = \left\{ \begin{array}{ccc} X & 0.5 & 1 \\ X & X & 1 \\ X & X & X \end{array} \right\}$$

(14)

$$\overline{irl}_1 = \text{mean}[irl_{12}, irl_{13}] = 0.75 \;,\; \overline{irl}_2 = \text{mean}[irl_{12}, irl_{23}] = 0.75,\; \overline{irl}_3 = \text{mean}[irl_{23}, irl_{13}] = 1.$$

(15)

The SRL vector is calculated from the products of the normalized *mrl,* average normalized *irl,* and TRL vectors using the formulas from Table 3, shown in equations (16) and (17).

$$\text{SRL}_i = mrl_i \; TRL_i \; \overline{irl}_i = \{0.66*3*0.75, 1*2*0.75, 1*4*1\} = \{1.49, 1.5, 4\}$$

(16)

$$\text{SRL} = \text{mean}[\text{SRL}_i] = 2.33$$

(17)

Analysis

SRL = 2.33 while the average TRL is 3, indicating a slight lag in at least one interface. From the normalized MRL, one can conclude that the system is at a mostly appropriate level of manufacturing readiness with two components at an *mrl* of 1 and one at 0.66. SRL_1 and SRL_2 are at 1.5, slightly lagging behind the technology readiness of 2 and 3 due to some interface development that needs to occur. $SRL_3 = TRL_3 = 4$ indicates that this technology is at an appropriate level of interface and manufacturing readiness. The metric indicates to management that it is time to devote additional resources to the interfaces of technologies 1 and 2 before pushing ahead in further component or system development.

It is very important to conduct the early phases of interface readiness, which involve subject matter experts from different fields exchanging information and ensuring that there exists an interface solution. If this is skipped, then at the demonstration and prototyping levels of 6.4 research, many technology choices must be revisited because the technologies have matured separately and are becoming incompatible. Revisiting technology choices may then result in program delays, cost overruns, or mad scrambles to prepare for demonstrations or program cancellations. The classic case of this is thermal management, when a new technology

becomes available with thermal management as an afterthought, and the legacy platform for which it is intended becomes overwhelmed with the new thermal load. The thermal issues associated with 5th generation aircraft (Majumdar & Kjelgaard, 2015) are a result of thermal interface as an afterthought. The opposite appears to be happening in the semiconductor industry in which thermal management is a very active area of research in anticipation of higher thermal loads on microchips in the near future.

Mid-level Technology with Lagging Interfaces

In a more abbreviated form than the previous example, we assume a simple, three-component system with components 1, 2, 3 funded at the 6.4 – demonstration level. MRL_i = {3,5,5}; TRL_i = {6,4,5}; $\overline{TRL}$ = 5, and the IRL has the following values: IRL_{12} = 3, IRL_{13} = 2, and IRL_{23} = 2. The SRL calculation is as follows:

mrl_i = {0.6,1,1}. irl_{12} = 3/5, irl_{13} = 2/5, and irl_{23} = 2/5, $\overline{irl}_1$ = mean[irl12, irl13] = 0.5 , $\overline{irl}_2$ = mean[irl_{12}, irl_{23}] = 0.5, $\overline{irl}_3$ = mean[irl_{23}, irl_{13}] = 0.4.

SRL_i = mrl_i TRL_i $\overline{irl}_i$ = {0.6*6*0.5,1*4*0.5,1*5*0.4} = {1.8,2,2}

SRL = mean[SRL_i] = 1.3

> *It makes no sense to continue and pursue more mature technology that may or may not work in the intended environment or with the other subsystems.*

Analysis

The fact that SRL = 1.3, but there are TRLs at 6 and 4 and an average TRL of 5, alerts management there are serious manufacturing and interface issues, probably due to neglect in early technical development. Note that the mrl_1 is 0.6 and is slightly lower than the other two; the SRL_i are very nearly all at 2; and the TRL_i are quite high—at 6, 4, and 5—due to the *irl* being much lower. This alerts management that emphasis needs to be placed on developing interfaces. Further component maturation is very risky and very likely counter-productive. It makes no sense to continue and pursue more mature technology that may or may not work in the intended environment or with the other subsystems. This system is headed toward program-killing safety, thermal, control, electrical, or other integration and deployment issues.

Advanced Technology with One Lagging Interface

The author assumes a simple, three-component system, with components 1, 2, and 3 funded at the 6.7 — operational systems development level. $MRL_i = \{7,7,7\}$; $TRL_i = \{7,7,7\}$ and the IRL has the following values: $IRL_{12} = 7$, $IRL_{13} = 7$, and $IRL_{23} = 4$. The SRL calculations are as follows:

$mrl_i = \{1,1,1\}$. $irl_{12} = 1$, $irl_{13} = 1$, and $irl_{23} = 0.57$, $\overline{irl}_1 = mean[irl_{12}, irl_{13}] = 1$, $\overline{irl}_2 = mean[irl_{12}, irl_{23}] = 0.79$, $\overline{irl}_3 = mean[irl_{23}, irl_{13}] = 0.79$.

$SRL_i = mrl_i \, TRL_i \, \overline{irl}_i = \{1*7*1, 1*7*0.79, 1*7*0.79\} = \{7, 5.5, 5.5\}$

$SRL = mean[SRL_i] = 6$

Analysis

SRL = 6, but the TRLs are all at 7. This alerts management that there is at least one interface or manufacturing issue. Examining the component SRLs reveals that $SRL_1 = TRL_1 = 7$, but the other two SRLs lag TRL, indicating that the interfaces from component 2 to 3 are lagging and should be addressed before developing the component technologies further.

Practical Example—High Energy Laser System

Note: This is an example and not representative of any particular system. A high energy laser system is in early research and development, primarily funded by 6.2 and 6.3 sources. It is composed of at least the following subsystems: laser, beam director (BD), thermal management (TM), electrical management (EM), structural support (Struct), atmospheric propagation (Atmos), target, target acquisition, tracking, pointing (ATP), and battle management and controls (BM). A TRL assessment might be as follows (Table 4).

Subsystem	Laser	BD	TM	EM	Struct	Atmos	Target	ATP	BM	Controls
TABLE 4. SAMPLE TRL/MRL RATINGS										
TRL	4	4	3	3	2	4	n/a	3	2	3
MRL	4	4	4	4	2	3	n/a	2	2	2

Note that the target TRL and MRL are "n/a" because the system does not involve building the target, but the atmosphere and ATP form an interface with the target so an IRL is associated with the target, but no TRL.

An IRL matrix might look as shown in Table 5, if most effort had been placed into developing the laser, beam director, ATP algorithms; and target information, but not much effort placed on 'system' issues, such as the electrical or thermal management systems or the controls architectures. For simplicity, only the upper half of the matrix is shown assuming that $IRL_{ij} = IRL_{ji}$.

TABLE 5. SAMPLE IRL RATINGS

IRL	Laser	BD	TM	EM	Struct	Atmos	Target	ATP	BM	Controls
Laser	X	2	1	1	2	n/a	3	3	1	3
BD		X	2	3	4	2.5	2	2.5	1	3
TM			X	4	4	n/a	n/a	4	4	4
EM				X	4	n/a	n/a	4	4	4
Struct					X	2	n/a	3	4	4
Atmos						X	2	2	n/a	n/a
Target							X	2	n/a	n/a
ATP								X	2	2
BM									X	2
Controls										X

Not every component has every kind of interface so that the n/a values in Table 5 are simply not part of the calculation. Applying the equations in Tables 1, 2, and 3 yields the results shown in Table 6, assuming normalization by the 6.3 funding values from Table 1 and Table 2. The SRL = 2.19. The average TRL = 3.1.

TABLE 6. SAMPLE IRL, MRL AND SRL COMPONENTS

Subsystem	Laser	BD	TM	EM	Struct	Atmos	Target	ATP	BM	Controls
$\overline{irl}_i$	0.67	0.81	1.1	1.14	1.13	0.71	0.75	0.91	0.86	1.05
mrl_i	1	1	1	1	0.5	0.75		0.5	0.5	0.5
SRL_i	2.67	3.26	3.29	3.43	1.13	2.13		1.36	0.86	1.57
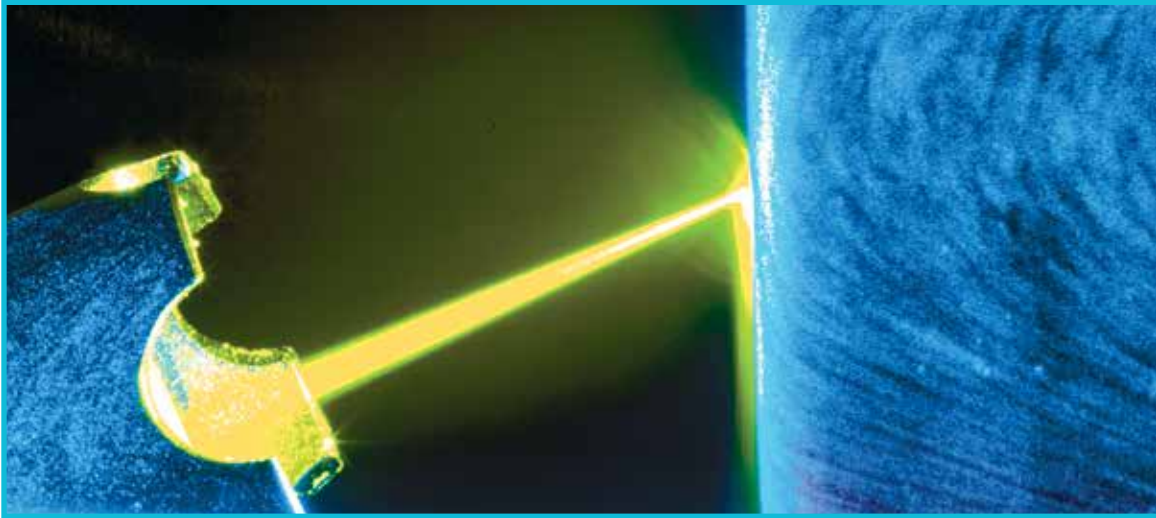
The average SRL is below the average TRL, indicating that there are some integration or manufacturing issues that should be addressed before the components are developed further. Specifically, the laser subcomponent itself is a TRL 4, with an appropriate level of manufacturability; however, its average IRL is the lowest of any of the other subsystems. Such a system is in danger of developing a main component that cannot be integrated, demonstrated with a prototype system at an appropriate level, or that will come up with extensive integration issues late in development. These integration issues may prove to be very costly and time-consuming to fix. It would be best to develop the laser-thermal, laser-electrical, laser-battle management, and laser control interfaces before continuing to mature the laser technology itself. The side benefit would be the ability to demonstrate early prototype laser systems rather than waiting for full maturity of the final laser to conduct any demonstrations, which would be conducive to maintaining the interest in funding this technology development effort.

Verbal System Readiness Level Definitions

The proposed mathematical definition of SRL permits a verbal definition of SRLs in a way that the Sauser definition and mathematics did not. There is one caveat to these verbal definitions: they strictly hold fast at those milestones of development where SRL = TRL. It is possible to have an SRL of 3 with TRLs of 6 by ignoring interfaces and manufacturing, in which case

the following definition of SRL = 3 (Table 7) would not be accurate because the SRL metric is significantly lagging the TRL metrics. This caveat also helps ensure that one cannot inappropriately claim a high level of SRL by having one mature component mask a less mature one.

SRL	Name	Definition
	TABLE 7. SYSTEM READINESS LEVEL DEFINITIONS	
1	System concept	The system concept has been identified to include the subsystems. Overall system functional requirements are qualitatively understood.
2	System technologies	Subsystem technology path identified to include a specific technology solution. Technology, manufacturing, and interface drivers understood.
3	System proof of concept	Experimental evidence has been obtained that the system is possible in principle to develop and manufacture.
4	System component verification	All system components have been built and tested in a laboratory environment separately. Numerical studies show component compatibility.
5	System component validation	All system components have been built and tested in a relevant or emulated production and deployment environment. Components with simulated interfaces have been tested.
6	System prototype demonstration	A system prototype has been demonstrated and fabricated in a relevant environment. Interface control has been demonstrated traceable to a deployed environment.
7	System operational demonstration	An integrated system prototype has been demonstrated and fabricated in an operational / manufacturing environment.
8	Actual system demonstration	The production representative system has been demonstrated in an operational environment.
9	Operational system	Production system is used, demonstrated, and maintained in an operational environment.

Generalized Integration Readiness Level Definitions

The author proposes the simplified critical item lists (Table 8) for the IRLs (U.S. Navy, 2009). The simplified lists allow a wider application to physical rather than IT systems, and focus on the few truly critical milestones rather than many contributing factors. See U.S. Navy (2009, p. 6) for a comparison.

TABLE 8. SIMPLIFIED INTEGRATION READINESS LEVEL DEFINITIONS

IRL	Name	(Sauser et al., 2010) Definition	Critical Items
1	Identification	An *Interface* between technologies has been identified with sufficient detail to allow characterization of the relationship.	• There exists a functional flow block diagram for the technology and its interfaces in a notional system concept. • Subject matter experts for each of the connecting technologies have been identified and a technical interchange held.
2	Characterization	There is some level of specificity to characterize the *Interaction* (i.e., ability to influence) between technologies through their interface.	• Input and output parameters have been identified for each interface.
3	Compatibility	There is *Compatibility* (i.e., common language) between technologies to orderly and efficiently integrate and interact.	• Parametric or physics-based models describe the interface at the qualitative level so that the impact on each of the identified parameters can be modeled at the system level. • Interface risks have been identified. • Interface constraints have been identified.
4	Quality and Assurance	There is sufficient detail in the *Quality and Assurance* of the integration between technologies.	• A solution space exists to meet design concept requirements. • Generic interface models have been validated by experiment.
5	Control	There is sufficient *Control* between technologies necessary to establish, manage, and terminate the integration.	• Interfaces are well defined. • Interfaces have been demonstrated in a laboratory environment. • Specific interface models have been validated by experiment.

TABLE 8, CONTINUED			
IRL	Name	(Sauser et al., 2010) Definition	Critical Items
6	Information	The integrating technologies can *Accept, Translate, and Structure Information* for their intended application.	• Control architecture is developed. • Software components work together. • Individual modules are tested with control signals to verify performance. • Integrated system demonstrations are completed.
7	Verification and Validation	The integration of technologies has been *Verified and Validated* with sufficient detail to be actionable.	• Fully integrated prototype in simulated operational environment. • Each interface tested under stressed and anomalous conditions.
8	Mission Qualified	Actual integration completed and *Mission Qualified* through test and demonstration, in the system environment.	• System is fully integrated in an operational environment. • All flight and safety qualifications are completed for all technologies and interfaces. • Form, fit, and function are verified.
9	Mission Proven	Integration is *Mission Proven* through successful mission operations.	• System is fully integrated and has demonstrated operational effectiveness. • Interface failure rates are fully characterized.

Use of the SRL Metric

Any time the performance or behavior of a complex system is summarized by a single number, there is inevitable loss of information and the potential for false indication. SRL and IRL have a subjective component to them, as do TRL and MRL. The existence of the SRL metric will not completely compensate for organizational or programmatic pressure to advance technologies prematurely to meet budget and schedule. It will, however, foster an awareness of the cost of doing so. The SRL metric, as defined herein, is designed to be an indication that a system or component is ready for the next step in development when the system readiness is commensurate with the technology readiness. From equations (5) and (11), where $SRL = \overline{TRL}$ at the system level and $SRL_i = TRL_i$ at the component level, advancement is appropriate. Since interfaces cannot be more mature than their component

technologies, SRL will lag TRL at each step of development. At that point, the program will move to a higher funding, maturity, or development category; the normalization factors will change; and SRL will once again lag TRL as shown conceptually in Figure 7. This built-in safeguard will reduce the possibility of a mature subset of the system overshadowing a less mature part and giving false indications (Kujawski, 2010). A further safeguard can be implemented by limiting the values of the normalized IRLs and MRLs (*mrl* and *irl* from Tables 1 and 2) to a maximum of 1.0, further ensuring that one mature component cannot mask a less mature one. The principle that advancement to the next level of funding or acquisition should not occur until the system readiness is commensurate with the technology readiness can and should be applied at the system level (when SRL = mean[TRL_i]) and at the component technology level (when $SRL_i = TRL_i$).

Conclusions

This article has proposed a modification to the Sauser mathematics of IRL and SRL that allows an SRL metric that gives a clear indicator of when a component technology or system is ready for further advancement and allows for standard verbal definitions of SRL. SRL and IRL need to be incorporated into the system engineering process early in development. TRL has been a valuable metric; however, its lack of emphasis on systems issues has resulted in divergent development, where some system components are developed beyond their interfaces and manufacturing, resulting in legacy decisions that impede demonstration and integration. A useful SRL metric can help to foster more balanced and cost-effective technology development.

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Appendix

Standard Technology Readiness Level and Manufacturing Readiness Level Definitions

TABLE A-1. STANDARD TRL DEFINITIONS	
TRL	Definition
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof of concept
4	Component and/or breadboard validation in a laboratory environment
5	Component and/or breadboard validation in a relevant environment
6	System/subsystem model or prototype demonstration in a relevant environment
7	System prototype demonstration in an operational environment
8	Actual system completed and qualified through test and demonstration
9	Actual system proven through successful mission operations

Note. (DoD, 2011)

TABLE A-2. STANDARD MRL DEFINITIONS	
MRL	**Definition**
1	Basic manufacturing implications identified
2	Manufacturing concepts identified
3	Manufacturing proof of concept developed
4	Capability to produce the technology in a laboratory environment
5	Capability to produce prototype components in a production-relevant environment
6	Capability to produce a prototype system or subsystem in a production-relevant environment
7	Capability to produce systems, subsystems, or components in a production-representative environment
8	Pilot line capability demonstrated; ready to begin Low Rate Initial Production
9	Low Rate Initial Production demonstrated; capability in place to begin Full Rate Production
10	Full Rate Production demonstrated and Lean production practices in place

Note. (DoD, 2012)

TABLE A-3. DoD STANDARD FUNDING CATEGORIES	
6.1	Basic Research
6.2	Applied Research
6.3	Advanced Technology Development
6.4	Advanced Component Development and Prototypes
6.5	System Development and Demonstration
6.6	RDT&E Management Support
6.7	Operational Systems Development

Note. (DAU, 2016)

Biography

Dr. Sean Ross has worked at the Air Force Research Laboratory, Directed Energy Directorate, since 1994. He is currently on a career-broadening assignment in the office of the Deputy Assistant Secretary of the Air Force for Science, Technology and Engineering. He is the author of "Laser Beam Quality Metrics" textbook and frequently teaches courses on the subject. Dr. Ross led the creation of the Environmental Laser Test Facility to test high-energy laser systems and components in simulated flight environments prior to flight testing. He has been involved in power, thermal, structural and other high-energy laser integration issues for over a decade. Dr. Ross holds a BS and MS in Physics from Brigham Young University and a PhD in Optical Science and Engineering from the Center for Research and Education in Optics and Lasers, College of Optics and Photonics.

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