

Technology Readiness Calculator

Abstract

DoD acquisition guidance as embodied in the Draft 5000 series publications requires that hardware and software-intensive systems exhibit an appropriate level of maturity as part of the entrance criteria at milestone decision points. Spiral development and evolutionary acquisition require mature technologies for incremental insertion into DoD systems. Section 804 of the FY2003 Defense Authorization Act requires the department to improve the software acquisition process by emphasizing maturity of software products offered to the government. There is no guidance on how to measure technology or product maturity. The NASA developed Technology Readiness Level (TRL) scale is an existing metric for describing technology maturity; however, there is no standard repeatable method for determining the TRL achieved by a given technology.

This paper reviews the NASA TRL scale to include TRL descriptions for hardware, software-intensive, and practice-based technologies. It then introduces a spreadsheet application that allows the user to answer a series of questions about a technology program. The spreadsheet calculates and displays the TRL achieved. The paper describes in detail the algorithms used to compute and display the appropriate TRL for a given technology. The final section of the paper outlines future work contemplated and required.

Why Measure Technology Maturity?

Since this paper's central topic is a tool for measuring technology maturity, let's first look at the larger question, "Why should we be interested in measuring the maturity of a technology at all?" In particular, why is technology maturity a subject for concern during the DoD system acquisition process? There are several reasons for measuring technology maturity as part of an acquisition or research and development program. We'll look at four of them here.

Best Practice – GAO

In a 1999 report [4], the General Accounting Office (GAO) showed that failure to properly mature new technologies in the science and technology (S&T), or laboratory, environment almost invariably leads to cost and schedule over-runs in acquisition weapons system programs. In their report, the GAO found [4, p.12] that separating technology development from product development is an industry best practice. The report puts it this way, "Maturing new technology before it is included on a product is perhaps the most important determinant of the success of the eventual product—or weapon system." This statement says that you must be certain that a technology is mature before including it as part of a product or weapon system. It leaves unanswered the question, "How do you know when a technology is sufficiently mature?" The report provides a recommendation [4, p.7]: "GAO recommends that the Secretary of Defense adopt a disciplined and knowledge-based approach of assessing technology maturity, such as TRLs, DOD-wide, and establish the point at which a match is achieved between key technologies and weapon system requirements as the proper point for committing to the development and production of a weapon system."

Risk Management

Measuring a technology's maturity provides one measure that can be an indicator of program risk. As the GAO report puts it [4, p.23], "Once a technology's readiness level has been established, the risks of including that technology in a product development can be assessed. Unlike S&T projects, for which the main objective is to develop knowledge, a product development's objective is to deliver products that meet strict cost, schedule, and performance targets." The report goes on to argue that a low level of readiness (low TRL) represents a high risk, because there are many unknowns that still need to be resolved in developing the technology. These unknowns create program risk because, until they are satisfactorily resolved, we don't know whether we can meet the program's cost, schedule, and performance goals. [4, p.24] "The gap between the maturity of the technology and the product's requirements represents the risks or unknowns about the technology." The GAO report tells us that measuring technology maturity in terms of the TRL can provide information useful in a weapon system risk management process. Moorhouse expands on these ideas by showing a mapping between TRL and degree of risk [13, p. 191]. He also demonstrates that the TRL can be an indicator of risk in the cost area, as well as in the technical performance domain.

Program Management

As the use of technology maturity in risk management demonstrates, measuring technology maturity can be helpful in the overall management of a program. In his article [13], Moorehouse states that TRL definitions can be used as exit criteria for program phases. More generally, knowing the current maturity of the program technology and comparing that to the required technology maturity can give the program manager an action plan describing activities that remain to be accomplished. The difference between where you are and where you need to be tells you what remains to be managed. We should note the obvious: the TRL scale doesn't tell us everything we need to manage a program. In fact, the TRL scale presents a one-dimensional view of technology maturity. According to a Software Engineering Institute study [10, p.9], the TRL scale only tells program managers "up to 30% of their decision criteria."

Mandate

There are both legislative and regulatory mandates that require DoD to measure technology maturity. Section 804 of the FY2003 Defense Authorization Act specifically directs each military department to improve its software acquisition processes. Paragraph (c) (2) (A) requires that acquisition programs consider software product maturity as a criterion during source selection. Product maturity is not defined.

DoD Directive 5000.1 repeats this mandate for software intensive systems [1, E1.25], "Selection of sources shall include consideration of product maturity and past performance." DoD Instruction 5000.2 also emphasizes technology maturity as an aspect of both spiral development and incremental development [2, 3.3.2.1 and 3.3.2.2]. The instruction says [2, 3.5.3] that technology maturity and technology maturation and demonstration needs must be considered during an analysis of alternatives. We are told [2, 3.6.5] that technology solutions must be "based on mature technology." In discussing the System Development and Demonstration phase of

procurement, DoD tells us [2, 3.7.2] that, “Entrance into this phase depends on technology maturity (including software).” We’re further informed two paragraphs later that “Technology readiness assessments, and where necessary, independent assessments, shall be conducted. If technology is not mature, the DoD Component shall use alternative technology that is mature and that can meet the user’s needs.” Technology maturity is mentioned several other times in the instruction and in its attachments, but nowhere does the instruction tell how technology maturity is to be measured.

The DoD Interim Guidance [3] is advisory, not directive, in nature; however, it does provide a more detailed explanation of the technology maturity measurement process [3, C7.5]. In particular, the Interim Guidance specifies technology readiness assessments. The guidelines for these assessments direct that TRLs (or some equivalent assessment) shall be used for determining technology maturity and for assessing program risk. A table providing TRL descriptions is given in an attachment [3, Appendix 6].

TRL Background

NASA Definitions

NASA has been using TRLs for many years [12, p. 1]. In one early form of TRL application [14], there were only seven different levels of technology maturity, measuring technical growth up to the start of a NASA flight program. The seven-level system reflected the development of a new technology. The current TRL descriptions define nine levels, adding TRL8 and 9 to carry technology maturity through mission operations. The TRL definitions published in the DoD Interim Guidance are essentially the same as the current NASA definitions [12], [3, Appendix 6]. These definitions are as follows: (DoD definitions given; NASA variations shown in parentheses, as applicable.)

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

While these are the official TRL Definitions, there can be a great deal of ambiguity in applying them to a specific technology development effort. For this reason, DoD has also published [3, Appendix 6] supplementary descriptions for each TRL. These descriptions augment the short

definitions given above. The definitions and descriptions are used with both hardware and software development programs, although further clarifications for software are permitted.

Hardware and Software Descriptions [3, Appendix 6]:

| | |
|--------------|---|
| TRL 1 | Lowest level of technology readiness. Research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties. |
| TRL 2 | Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies. |
| TRL 3 | Active research and development is initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative. |
| TRL 4 | Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared to the eventual system. Examples include integration of "ad hoc" hardware in the laboratory. |
| TRL 5 | Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment. Examples include "high fidelity" laboratory integration of components. |
| TRL 6 | Representative model or prototype system, which is well beyond that of TRL5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high fidelity laboratory environment or in simulated operational environment. |
| TRL 7 | Prototype near or at planned operational system. Represents a major step up from TRL6, requiring demonstration of an actual system prototype in an operational environment, such as in aircraft, vehicle, or space. Examples include testing the prototype in a test bed aircraft. |
| TRL 8 | Technology proven to work in its final form and under expected conditions. In most cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of the system in its intended weapon system to determine if it meets specifications. |
| TRL 9 | Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation. Examples include using the system under operational mission conditions. |

The DoD Interim Guidance also includes definitions of some of the terms used in these descriptions.

Program Readiness for Transition

A technology's maturity alone doesn't tell us everything we need to know about how a program is progressing. There are many programmatic concerns that are important, but don't directly affect the technical side of the project. These include such things as identifying potential customers and creating the necessary program documents. While these tasks are essential to the

program's success, they reflect more managerial aspects of a research program, and not the purely technical factors that a TRL traditionally measures.

Early versions of the calculator computed a single value of the TRL achieved. Some users observed that a few questions addressed topics not directly relevant to technology maturity. When we said that we could just delete these questions, the users stated that the questions should be retained because they are important in managing a technology development program. The programmatic questions were segregated from the pure technology questions to reflect their separate nature. The name, Program Readiness for Transition (PRT), was chosen to highlight the programmatic nature of the questions covered.

The Application Problem

We have seen above that there are several reasons for using TRLs. Probably the most compelling, from a DoD viewpoint, is that determination of technology maturity is mandatory. DoD "Must Do" technology maturity measurement by legislative and regulatory decree. The application problem arises from the fact that, although "Doing" technology maturity is directed, there is no "How To" information given [11, p. 2]. The Interim Guidance says [3, C7.5.3], "TRLs (or some equivalent assessment) shall be used." There is a complete lack of detail on implementation.

The TRL Calculator: What is it?

The TRL Calculator is a tool for applying TRLs to technology development programs. In its present form, the calculator is a Microsoft Excel spreadsheet application that allows the user to answer a series of questions about a technology project. Once the questions have been answered, the calculator displays the TRL achieved. Because the same set of questions is answered each time the calculator is used, the calculator provides a standardized, repeatable process for evaluating the maturity of any hardware or software technology under development. In this way, the TRL Calculator is one tool that can serve to answer the "How to?" problem discussed above.

The TRL Calculator: What does it do?

In applying the TRL concept, the calculator provides a snap-shot of what a technology's maturity level was at a given time. It is a historical view of the technology's development [5, p.9]. While the TRL can tell us what has been done up until that time, knowing that a program has achieved a certain TRL tells us nothing about its prospects for future growth. The current TRL gives no information on risk; nor does it tell us anything about the likelihood of reaching a higher TRL. A standard method of judging technology maturity can give a program manager a significant amount of information about the overall program risk. This is because, in general, a mature technology presents fewer risks for implementation than an immature technology does. The TRL Calculator can be a useful tool in a risk management program. It can also help in the overall program management of a technology development effort because it tells management the current state of the program's technology maturation process. The calculator's questions and per cent complete feature can assist a program manager in tracking progress toward accomplishing required tasks.

Weighted TRL

The weighted TRL is an attempt to include the relative importance of different categories of questions. The unweighted TRL computed and displayed by the calculator treats all question categories equally. By contrast, the weighted TRL allows the user to assign different weights to different categories of questions. The different weights represent different levels of importance for the question categories. For example, setting one category weight at 2 and another at 4 says that the second category is roughly twice as important as the first. The calculator can then compute a weighted TRL reflecting the relative importance placed on the various areas covered by the calculator's questions.

In most cases, it probably isn't necessary to bother with the weighted TRL. In the default condition, the weighted TRL is not displayed. As mentioned above, the weighted TRL lets you see the effect of differing degrees of importance in the separate question categories. The weighted TRL can also help in performing "What if?" analyses. Setting a category weight equal to zero eliminates that category from the TRL computation. By assigning all other categories the same weight, you can see what TRL would result from ignoring the zero weight question category completely.

Program Readiness for Transition

We introduced the concept of PRT above. The calculator measures PRT on a separate, linked worksheet. Placing these programmatic questions on a separate worksheet let us easily create different versions of the calculator, one including programmatics, and one without. The calculator treats TRL and PRT as separate but related entities. One can think of PRT and TRL as measuring two different dimensions of a program's maturity.

While the PRT is computed separately from the TRL, the two are nevertheless linked. Since it would be impossible to transition a technology that doesn't exist, the PRT calculator gives priority to the TRL computation. When the PRT is calculated, it will never display a higher value than the TRL value computed on the linked TRL worksheet.

Another quirk of the present version of the calculator is that PRT is limited to a value corresponding to TRL6 or lower. This is because, in AFRL, the stated objective of a technology development program is to mature the technology to TRL6 [4, p.2]. While it is certainly possible to mature a given technology beyond that level, there are no purely programmatic activities that take place within the laboratory beyond TRL6. Because the calculator was initially created for use in the lab, a PRT of 6 was deemed sufficient. Extending the PRT concept to a level corresponding to TRL9 is a subject for future work.

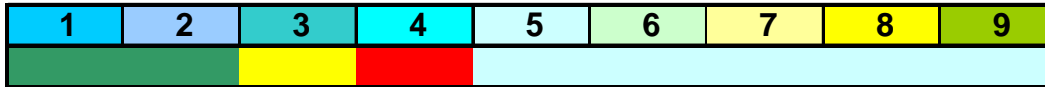
The TRL Calculator: Under the Hood

Now that we have introduced the TRL calculator, let's see how it works. This section of the paper goes into the inner workings of the calculator. In this discussion, we use the term TRL to mean both TRL and PRT, since the two worksheets work the same way. We'll first look at the

structure of the calculator. Then we'll examine the decision algorithms that drive the TRL calculations.

Structure

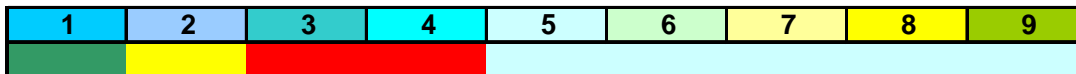
When you look at the calculator, you'll see that there is a segmented thermometer display running horizontally across the top of the page. As you scroll down the page to enter or review data, the display area will remain in view at the top of your monitor screen. The display segments beneath the TRL numbers change color as data is entered into the spreadsheet.



The colored segments indicate the overall TRL achieved according to the following color code:

| Color | Meaning |
|--------|---|
| None | No data has been entered at this level or higher |
| Red | Some data has been entered at this level or higher, but not enough to claim attainment of this level |
| Yellow | While there are still items that have not been completed at this level or below, you may be able to claim attainment of this level, depending on the importance of the unfinished items to your program |
| Green | This level has been reached |

Note that the display will never show a greater degree of completion at a higher level than the minimum achieved below that level. Example: TRL2 = yellow, TRL3 = red, TRL4 could be green (all level 4 questions checked), but will score as red because that's the limiting score achieved at a lower level.



If enough tasks get done at TRL3, the TRL 3 & 4 displays could both change to yellow, but neither could "Go green" until enough TRL2 tasks are done to change that level to green.

The display also includes fields where the TRL attained at both the "Yellow" and "Green" degrees of completion is shown numerically instead of graphically. These cells are located above the horizontal thermometer TRL7 and TRL8 positions. This feature allows the TRL achieved to be readily exported from the TRL calculator to other software tools.



There is also a numeric display of the weighted TRL, if calculated.

Below the display is the "Question and answer" area of the calculator. Here is where the user answers detailed questions about the program and/or technology. There are basically two methods of answering the questions. Some questions are answered by checking a check box.

| % Complete | | Level of Knowledge (Check all that apply) | |
|------------|-------|---|---|
| ◀ | ▶ 100 | <input checked="" type="checkbox"/> | Basic scientific principles observed |
| ◀ | ▶ 40 | <input type="checkbox"/> | Possible application exists |
| ◀ | ▶ 95 | <input type="checkbox"/> | Paper studies confirm basic principles |
| ◀ | ▶ 60 | <input type="checkbox"/> | Paper studies show that application is feasible |
| ◀ | ▶ 80 | <input checked="" type="checkbox"/> | Physical laboratory experimental evidence confirms basic principles |
| ◀ | ▶ | <input checked="" type="checkbox"/> | Laboratory experiments verify feasibility of application |
| ◀ | ▶ | <input checked="" type="checkbox"/> | Rigorous analytical studies confirm basic principles |
| ◀ | ▶ | <input checked="" type="checkbox"/> | Physics underlying the technology is well understood |
| ◀ | ▶ | <input checked="" type="checkbox"/> | Overall system requirements for end user's application are known |
| ◀ | ▶ | <input type="checkbox"/> | Science known to extent that mathematical and/or computer models and simulations are possible |
| ◀ | ▶ | <input type="checkbox"/> | System interface requirements known |
| ◀ | ▶ | <input type="checkbox"/> | Operating environment for eventual system known |

A checked box means that the task the question is asking about has been done. Some of these questions allow the user to enter the percent complete, using a slider bar. Percent complete tracking may be used as a program management aid. Once the percent complete equals or exceeds the threshold value assigned by the user, the task is counted as done in the calculator's computation, just as if the check box had been checked. Questions using the check box method of answering will be grouped together into categories where the user is asked to check all that apply.

Other questions are answered by selecting the one best answer from a list of options. In this case, the directions will say something to the effect of "Pick the best answer." The selection from the group of related questions is made by clicking on the correct radio button.

| Components (Pick the best answer) | |
|-----------------------------------|--|
| <input type="radio"/> | No system components, just basic laboratory research equipment to verify physical principles |
| <input type="radio"/> | Ad hoc and available laboratory components are surrogates for system components |
| <input checked="" type="radio"/> | Some special purpose components combined with available laboratory components |
| <input type="radio"/> | Components are functionally compatible with operational system |
| <input type="radio"/> | Components are representative of production components |
| <input type="radio"/> | Components are form, fit, and function compatible with operational system |

You won't be able to select more than one response in any one of these categories of question. Picking one radio button automatically turns off any previously selected button.

Each question on the calculator is associated with one, and only one, TRL. These TRL associations are concealed in hidden columns on the calculator spreadsheet. The figure shows the TRL associated with each question in the, "Level of Knowledge" category. For example, the question reading, "Paper studies confirm basic principles" is associated with TRL1, while the question that says, "Paper studies show that application is feasible" is tied to TRL2. These TRL associations are used in the computation of category and overall TRLs as will be shown below.

| Level of Knowledge (Check all that apply) | | TRL |
|---|---|-----|
| <input checked="" type="checkbox"/> | Basic scientific principles observed | 1 |
| <input type="checkbox"/> | Possible application exists | 2 |
| <input type="checkbox"/> | Paper studies confirm basic principles | 1 |
| <input type="checkbox"/> | Paper studies show that application is feasible | 2 |
| <input checked="" type="checkbox"/> | Physical laboratory experimental evidence confirms basic principles | 3 |
| <input checked="" type="checkbox"/> | Laboratory experiments verify feasibility of application | 3 |
| <input checked="" type="checkbox"/> | Rigorous analytical studies confirm basic principles | 2 |
| <input checked="" type="checkbox"/> | Physics underlying the technology is well understood | 3 |
| <input checked="" type="checkbox"/> | Overall system requirements for end user's application are known | 4 |
| <input type="checkbox"/> | Science known to extent that mathematical and/or computer models and simulations are possible | 3 |
| <input type="checkbox"/> | System interface requirements known | 5 |
| <input type="checkbox"/> | Operating environment for eventual system known | 6 |

We could have arranged the questions in order of increasing TRL. Instead, we chose to group them into categories of related questions. By grouping related questions together, the spreadsheet forces the user to consider all of the questions relevant to a particular topic at the same time. This helps prevent confusion, since all of the questions that ask about “Level of Knowledge” are covered before moving on to “Components,” “System Integration,” etc. The advantage of this arrangement is that you see all related questions together, and you don’t have to remember what you answered earlier on the worksheet to respond logically to a later question. The disadvantage is that you’ll have to run through the entire spreadsheet, answering all relevant questions in every category, before the calculator can compute even a very early TRL value.

To the right of the questions for each category, there is a place to enter the category weight in the field labeled “Wgt.” Using the “Up” or “Down” arrows provided, you can increase or decrease the category weight from 0 through 5 to reflect the relative importance of this category as compared to other categories. The category weights are used in computing the weighted TRL. If any number other than 0 is entered, the block turns green, showing that this category is included in the calculation of the weighted TRL. The two figures below show a weight of 0, and a weight of 2. The mathematics for computing the weighted TRL is covered below.

| | |
|---|-------|
| ▲ | Wgt |
| | 0 |
| ▼ | TRL 4 |

| | |
|---|-------|
| ▲ | Wgt |
| | 2 |
| ▼ | TRL 4 |

Directly below the category weight field is a blue field that displays the TRL achieved by that category, without considering the contribution of data entered

under any other question category. The category TRL can be an aid in identifying limiting factors. For example, if all of the category TRLs display a TRL5 or TRL6, but System Integration is only a TRL3, that fact could indicate an area where management attention is needed.

We saw above that some questions allow the user to enter the percent complete for a given task. There we said that when the percent complete was set high enough to meet or exceed the user designated threshold, that question would be included in the TRL computation. Now let’s take a look at how the user sets the threshold. To the left of the thermometer display at the top of the page is a block labeled, “% Complete is now set at.” Using the arrows next to the data block, you

| | |
|---|---------------------------|
| ▲ | % Complete is now set at: |
| ▼ | 80% |

can set the threshold for any value from 5% to 100%. The background color of the block shows generally what value is set for the threshold. At 50% and below, the block is red. From 55% to 80% (as in the figure), the block turns yellow, and for 85% or more, it will be green. If you try to set the threshold at 0%, it jumps to the default value of 80%.

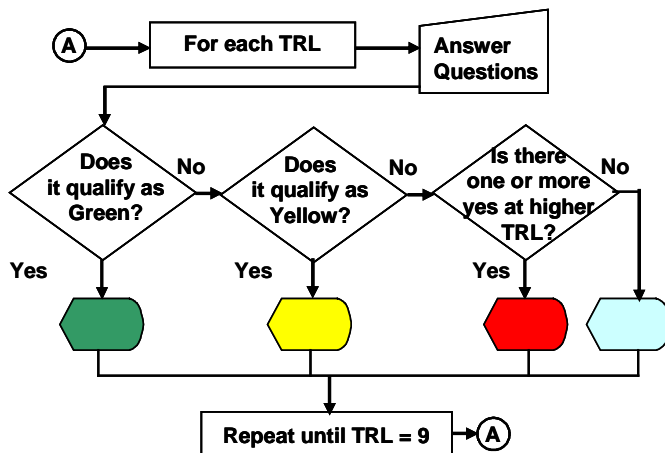
At the top of the spreadsheet, you'll find this block:

[Read TRL Documentation](#)

The block contains a hyper-link that moves you to the calculator documentation menu. The links on the documentation menu will give you access to background information about TRLs, including hardware and software TRL descriptions as well as papers and reports authored by people at NASA and the Software Engineering Institute. There is also a link to the web site that contains the 1999 GAO report that kick-started DoD in its use of TRLs. Most of the documents are included with the TRL Calculator package. Of special note is the link to the Color Code. That page contains the instructions for operating the calculator.

Decision Algorithms

Overall TRL



The figure shows the top level decision algorithm used to display the overall TRL graphically, using Red, Yellow, Green, and No Color.

The qualifying algorithm looks at the number of questions checked and the color of the previous TRL, except for TRL1 which has no previous. Checking the previous color keeps the calculator from displaying a green TRL at a higher level than a red or yellow, and keeps a yellow from appearing higher than a red.

The algorithm is:

Display green if everything below this level is green, and there are enough questions at this level checked to justify green.

Display yellow if the previous level is yellow and you have answered enough questions at this level to justify a green or yellow rating. Display yellow if the previous level is green and this level has enough questions answered to justify yellow, but short of the number needed for green.

Display red if there is at least one question answered at this level or higher, but it doesn't meet the green or yellow criteria.

If no question has been checked at or above this level, leave the space blank.

The TRL1 algorithm can be stated as:

If

Count at TRL1 is greater than $0.8 * \text{number of questions associated with TRL1}$

Then

Display color for TRL1 = Green

Else if

```

    Count at TRL1 is greater than  $0.67 * \text{number of questions associated with TRL1}$ 
  Then
    Display color for TRL1 = Yellow
Else if
  Total count of all TRLs is greater than 0
  (At least 1 question checked at this TRL or higher)
  Then
    Display color for TRL1 = Red
Else
  Display color for TRL1 = No Color
End if

```

The algorithm for all other TRLs is similar, except it checks the color of the previous TRL:

```

If
  Count at this TRL is greater than  $0.8 * \text{number of questions associated with this TRL}$ 
And
  Display color at previous TRL = Green
  (Check color at prior TRL)
Then
  Display color for this TRL = Green
Else if
  Count at this TRL is greater than  $0.67 * \text{number of questions associated with this TRL}$ 
And
  Display color at previous TRL = Green
Or
  Display color at previous TRL = Yellow
  (Check color at prior TRL)
Then
  Display color for this TRL = Yellow
Else if
  Total count of all TRLs is greater than Total count at previous TRL
  (At least 1 question checked at this TRL or higher)
  Then
    Display color for this TRL = Red
Else
  Display color for this TRL = No Color
End if

```

Once the calculator has computed the display colors according to the above algorithms, the MSExcel Conditional Formatting capability is used to put the proper background color in each cell of the horizontal thermometer display. A look-up table finds the highest TRL checked Yellow or Green, and puts the numeric TRL values into the yellow and green cells labeled “Technology Readiness Level Achieved.”

Category TRL

Category TRLs are calculated in two different ways. Where the user is instructed to, “Check all that apply,” we count all the “Hits,” or checked boxes, on each TRL1, TRL2, ..., TRL9 within a category and see how this number of hits compares to the total number of questions possible at that level. Consider the following: The first question category on the Hardware TRL Calculator is “Level of Knowledge.” The twelve questions in the category, along with their associated TRLs, were shown above. There are no questions in this category associated with TRL7, 8, or 9. Let’s put all of this into a table with some notional data entered.

| TRL | Number of Questions at this TRL | Minimum Number of Hits Required at this TRL | Alternate: Minimum Total Number of Hits Required, All TRLs | Hits | Was this TRL achieved? 1=yes 0=no |
|------------|--|--|---|-------------|--|
| 1 | 2 | 1 | 3 | 0 | 1 |
| 2 | 3 | 2 | 5 | 2 | 1 |
| 3 | 4 | 3 | 8 | 4 | 1 |
| 4 | 1 | 1 | 10 | 1 | 1 |
| 5 | 1 | 1 | 11 | 0 | 0 |
| 6 | 1 | 1 | 12 | 1 | 1 |
| Total | | | | 8 | TRL5 |

For each TRL in the category, if either the “Minimum Number of Hits Required at this TRL,” or the “Alternate: Minimum Total Number of Hits Required, All TRLs” is met, that TRL level is assumed to have been met. The “Minimum Total Required” feature prevents the calculator from failing to give proper credit when a few of the early questions were missed. This would place undue weight on a few questions when the majority of questions within a category are met. The category TRL is the sum of all the scores in the last column of the table.

From the above table we can see that TRL1 received a score, even though there were no hits. The score came from the total number of hits being equal to or greater than 3. TRL2, 3, 4, and 6 each got a score because the minimum required criterion was satisfied. TRL5 receives a 0 because neither decision criterion was met. Adding up the 6 TRL scores contained in the last column gives a sum of 5, and this would be displayed in the Category TRL field of the calculator.

The question categories that say, “Pick the best answer,” are answered with radio buttons. These categories have a simpler decision algorithm. Each button position is associated with one, and only one, TRL level. Whenever a button is checked, the calculator displays the Category TRL associated with that button. Let’s look at the ten buttons in the “System Integration” category.

| System Integration (Pick the best answer) | | TRL |
|---|--|-----|
| <input type="radio"/> | No attempt at integration; still trying to see whether individual parts of the technology work | 2 |
| <input type="radio"/> | Paper studies indicate that system components ought to work together | 3 |
| <input type="radio"/> | Laboratory experiments with available components show that they work together (lab kludge) | 4 |
| <input type="radio"/> | Available components assembled into system breadboard | 4 |
| <input type="radio"/> | Interfaces between components/subsystems are realistic (Breadboard with realistic interfaces) | 5 |
| <input type="radio"/> | Fidelity of system mock-up improves from breadboard to brassboard | 5 |
| <input type="radio"/> | Laboratory system is high-fidelity functional prototype of operational system | 6 |
| <input type="radio"/> | Prototype improves to pre-production quality | 7 |
| <input type="radio"/> | System is form, fit, and function design for intended application and weapon system platform | 8 |
| <input checked="" type="radio"/> | System has been installed and deployed in intended weapon system platform | 9 |

From the figure we can see that clicking on the top button (position 1) will cause the calculator to display a category TRL of 2. Clicking on either button three or four will display TRL4, button 9 displays TRL8, etc. With the last button clicked as in the figure, the Category TRL will display TRL9 as shown here.

| |
|-------|
| Wgt |
| 0 |
| TRL 9 |

Weighted TRL

The weighted TRL, should you choose to use it, is computed from the category TRL and category weights. Calculation of the category TRL was described above. Entering the category weights, representing relative importance of the various question categories, was also explained earlier. The calculator uses these two values to compute the weighted TRL. Both of these are required for a question category to be included in the weighted TRL computation. If the category weight is set to 0, or if there is no data entered in any question in the category, that category is eliminated from the weighted TRL.

The calculator computes the weighted geometric mean for all question categories that have both a non-zero category TRL and a non-zero category weight. Let the question categories be assigned category weights, w_i , where $i = 1$ to n , n being the number of categories included in the calculation. Let the category TRLs, L_i , be computed as above. The weighted geometric mean gives the overall weighted TRL as $TRL_{wgt} = \sum \sqrt{\prod L_i^{w_i}}$. Note that this formula automatically results in the elimination of any category TRL with a zero weight. This is because, for a given category i , if $w_i = 0$, then $L_i^0 = 1$. The product under the radical is unaffected by multiplication by 1, and the root (sum of the weights) is unaffected by adding a 0.

Linkage between PRT and TRL

When the PRT concept was first introduced above, we said that the PRT would never display a higher numeric value than the TRL value calculated separately. Let's look at an example. For notional program data, the calculator computes the following TRL:

| Technology Readiness Level Achieved | | | | | | 2 | 1 | |
|-------------------------------------|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| | | | | | | | | |

Note that the Yellow and Green levels achieved are TRL2 and TRL1 respectively. How does this affect the PRT? Take a look at the PRT calculations displayed here:

| Program's Readiness for Transition | | | | | | 2 | 1 | |
|------------------------------------|---|---|---|---|---|--|---|--|
| 1 | 2 | 3 | 4 | 5 | 6 | Note that the PRT above is never greater than the TRL. | | |
| | | | | | | | | |

Even though the graphical thermometer scale shows that the program PRT is Green at PRT3 and Yellow at PRT4, the numeric PRT boxes display 2 in the yellow box and 1 in the green box. These numbers came from the TRL calculation.

Next Steps

Formal Statistical Validation

If the calculator is to be of real value to the community, we need to perform a formal verification and validation of the product. One method of performing a statistically valid verification would be to use the scaling process central to the field of Psychometrics. “Scaling is the branch of measurement that involves the construction of an instrument that associates qualitative constructs with quantitative metric units. Scaling evolved out of efforts in psychology and education to measure ‘unmeasurable’ constructs ...” [15] Ideally, we’d like to start at “Square One” and revalidate the entire TRL scale, not just the calculator [9]. We may find that this ideal is not attainable, because the 9 level TRL scale is too entrenched in the acquisition culture. In this case, we’ll try to apply the principles of Psychometrics to the validation of the calculator itself to make sure that we’re asking the right questions, and that the decision algorithms give the correct results.

Extend PRT to Level 9

We showed above that, at present, the PRT computed by the calculator is limited to a maximum value of 6. There are programmatic activities that take place above this level. Adding the necessary questions to extend the PRT concept to level 9 is possible. The additional information available to program managers working in the later stages of product development probably makes the effort worthwhile, so we’re planning on making this PRT extension a part of some future effort.

Manufacturing Readiness Levels

The calculator currently measures two dimensions of technology maturity. These are the TRL, measuring the technology itself, and the PRT which measures programmatic issues. To these, we could add producibility, since a technology that can’t be manufactured is useless. As Dan Cundiff, ODUSD(AS&C), observed [6], “While the TRL approach is a valuable tool to evaluate prototype components based upon performance demonstration, this approach, as currently applied, does not require the prototype components to be producible, reliable and affordable. The concept of Manufacturing Readiness Levels, or MRLs, evaluates the ‘manufacturing readiness’ of a technology and its associated product and/or process technologies (hardware or software) that comprise components, subsystems, and systems.” He proposed the use of MRLs to augment TRLs in determining the overall maturity of a technology [7], [8]. Mr. Cundiff’s solution would augment the TRL descriptions to include MRLs. An alternate approach would be to measure MRLs as an additional dimension of technology maturity, as we did for PRT. We are proposing this alternate approach as a subject for future effort in refining the calculator.

Practice Based Technologies

The latest TRL Calculator, version 1.12, allows users to determine the TRL of either hardware or software technology. The Carnegie-Mellon Software Engineering Institute (SEI) has done some preliminary work on applying the TRL concept to practice based technologies (PBT) [10]. SEI defines PBTs as technologies that deal with, “Practices, Processes, Methods, Approaches, and Frameworks (for the above).” In the preliminary work, SEI shows that, as a technology matures, the community of users expands from initial risk takers to more mainstream members of the community, and the technology progresses from defined basic properties through defined core practices, implementation mechanisms, best practices, to a body of knowledge. A future release of the calculator will include a capability to measure the TRL of PBTs.

Calculator Structure Enhancements

We also plan to add some features to the current calculator layout. For example, we plan to insert fields where the user can provide program identifying information. We also plan to give the user space to enter comments in each category. We intend to give the user an opportunity to add questions, either within a category, or as one or more completely new categories of questions. These enhancements should help make the calculator more useable to a wider constituency.

Convert from Spreadsheet Application to Stand-Alone Executable

As a long-term project, we would like to make the calculator more device and software independent by rewriting it as a stand-alone executable program. The goal would be to create a product that can run on any platform, under any operating system, without requiring the purchase of a specific software package (in this case, Microsoft Excel).

Conclusion

AFRL has developed a TRL Calculator that has proved to be useful in applying the TRL concept to research and development programs. The calculator simplifies the process of determining the appropriate TRL for a given technology. By presenting a standard set of questions to every user, the calculator makes the process more repeatable. The standard format facilitates the comparison of different technologies, and will accommodate both hardware and software development programs. Within DoD, the use of technology maturity measures has been mandated, both legislatively and by regulation. The TRL Calculator was created in an attempt to answer the question, “How should technology maturity be measured?” We believe that the attempt was successful.

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