Technology readiness levels use and understanding

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Abstract Technology Readiness Level (TRL) is commonly used to evaluate the maturity of the technology in research and development projects. For this paper, a literature study has been performed in combination with a survey, to try to understand whether and how TRLs are used. Existing knowledge on the value of TRL will be collated and reviewed. It will also be considered to what degree the TRL evaluations are suitable for small organizations without separately trained and skilled readiness assessment personnel.

Introduction

The technology readiness scale is to some degree mystical from an engineering viewpoint, the scale is ordinal in nature, and a level is given simply by reaching a technical milestone, such as a e.g. a simulated test of a prototype. This is fascinating in an engineering view, as meters and other measurements normally applied in engineering are strictly logical, and have a set difference, in some way or another. When writing this thesis, the goal was to create a better understanding why, and how this scale works.

Background

History Technology readiness levels (TRL) is a system engineering tool that is intended to perform maturity evaluation of technology. It originated from National Aeronautics and Space Administration (NASA). The metric was created by Stan Sadin, and was formalized after years of testing (Sadin, Povinelli, & Rosen, 1989). Experience later show that the TRL scale has proven to be very useful in achieving delivery quality, based on the understanding that delivery quality is a product of cost and schedule. TRL was originally created to achieve a "mutual agreement between research personnel, research management, and mission flight program managers" at NASA (Sadin, Povinelli, & Rosen, 1989). This was done to be able to differentiate technology maturity in a discipline independent way. The original definition of TRL was a scale from 1, that could be a back-of-an-envelope-model defining basic ideas and concepts – to 7 which include a system prototype demonstration in space environment (Sadin, Povinelli, & Rosen, 1989). The method was later appended to include up to 9 levels (Mankins J. C., 1995) which is the currently prevalent model. An additional 10^{th} level was recommended, (Straub, 2015), but has also previously been discussed together with a TRL 11 (Hicks, Larsson, Culley, & Larsson, 2009), as a way to make the Technical Readiness Assessment (TRA) more commercially available.

Risk The TRL scale has among other been considered a picture of the remaining technical risk of a project. Due to the limitations on the measurements scale; there are several factors that also impact risks that are not a part of the TRA, still the technology readiness scale is used as a part of the basis for decision making in projects and programs.

Resources evaluations based on the TRLs do happen, however the effects of TRL on the cost and schedule is normally used indirectly via the remaining technical risks, rather than as a predictor of cost and schedule frames, independent of risk.

Suitability It is evident from the persistent use of TRLs that the scale has some elements of contribution. The third consideration that intrigues with regard to the TRL scale is why and how it works. How do people understand this maturity measurement? Why is it or is it not used? From a systems engineering (SE) viewpoint; how could it affect the way people work within projects?

Research questions: The unanswered questions above have led to a formulation of research questions that have been used as a basis for how the research to this paper was conducted. During the paper these questions will be attempted answered.

- TRL can be stated in requirements, does this drive the need for systems engineering?
- TRL can be used to determine risk in the program, does this drive the need for systems engineering?
- TRL often contributes to determination of budget and schedule parameter, does this drive the need for systems engineering?

Methods

A methodological fit may be considered as an "internal consistency among elements of a research project" (Edmondson & McManus, 2007).

The overarching framework for this inquiry is the technology readiness assessment (TRA) and resulting TRLs.

Literature review was performed to show what has previously been discussed and concluded with regard to the use of TRLs. Academic literature and publicly available documentation from user organizations have been used as a basis, as this in parts is also a practical endeavor.

For possible replication of this work; the sources used for the research is naturally the school's own library (www.usn.no). The library subscribes to some but not all of the following of the used sources; Sciencedirect, Elsevier, ResearchGate, Googlescholar, government/organization webpages, Search phrases used ranged from Technology readiness levels (TRL), Technology readiness assessment (TRA), new product development, different reference authors names. Risk TRL, ITAM, TRRA, TPMM, Risk uncertainty, 12 roles, ordinal TRL scale, cardinal TRL scale, capability readiness, integration readiness levels, innovation readiness levels, manufacturing readiness levels, SRL, best practice defense acquisition, API 17N, DNV-RP-203A.

A content analysis was performed to compare the information gathered about the different TRL levels to try to understand how it is talked about in academia, and how it is represented in the user organizations. As NASA was the originator of the TRL scale, it would not be logical to leave feedback from organizations like NASA and others out. As a basis for the content analysis the 9 level TRL scale is presented as a basis with a main focus on the NASA statements. Some versions of 7 level scales, such as represented in (American Petroleum Institute, 2009) (DNV GL AS, 2017), exist, but these have been excluded from the content analysis, as they do not match the more commonly used TRL scales.

A Survey was performed in order to see what the commoner, working in new product development or related to systems engineering considers to be reasonable surrounding the TRLs. Survey response were collected trying to pinpoint:

- The intuitivism of the different TRL levels
- The knowledge about the use of TRLs
- To what degree the respondents thought TRL or other forms of maturity metric may be suited as a basis for evaluations that effect progress of a project or program.

The survey was spread among contacts, mainly working with new product development, and a link was posted on the INCOSE website. The respondents were asked not to look up the TRL scale before they completed the survey. The survey created to be suited for technical personnel, technical management; at all levels from assembly to e.g. business, innovation, and portfolio managers. The results presented have been sorted so that persons that both confirmed and repudiated the same statement were removed. Answers hastily filled with the same answer throughout the survey have also been removed in order to avoid noise to the result. The questions were prepared in Norwegian and English. After the survey two questions were removed, as the translation was too weak.

Limitations in the study Within the documentation used in this study, it is necessary to express that most of the research on TRLs is based on numbers from US Government Agencies based on a rather limited number of programs. (Gatian, 2015), (Dubos, Saleh, & Braun, 2008), (Dubos & Saleh, 2011) (Engel, Dalton, Anderson, Sivaramakrishnan, & Lansing, 2012), (Azizian, Sarkani, & Mazzuchi, 2009), (Katz, Sarkani, Mazzichi, & Conrow, 2015), (Meier, 2008) have either used numbers directly from NASA's "Resource Data Storage and Retrieval data base "(REDSTAR) for their studies or used the (Lee & Thomas, 2001) study as a basis, which eventually is numbers from the same database. The knowledge captured in the above-mentioned studies are colored by the environment in which the information is gathered, but they may still give an indication of the value of TRL.

Triangulation The content analysis and survey will be discussed and consider by triangulation towards published academic literature and user organization documentation.

Results

Literature study

Risk. The TRL of a Critical Technology Elements (CTE) in a project or program indicates an assumed level of the remaining technical risks for the independent technology. In guides, this is referred to as in an indirect way such as "development hurdle" (ESA, TEC-SHS, 2008), (Mankins J. C., 2009) or "maturity gap for successful inclusion" (U.S. GAO, 1999). The TRA is a tool created to overcome the difficulty of comparing disciplines-specific metrics when measuring the feasibility of products cross-discipline (Sadin, Povinelli, & Rosen, 1989). As most of the literature presented here will be based on U.S. governmental agencies numbers, it is necessary to first consider what a suitable level of maturity for integration is accordingly. The technical maturity on a discipline independent level can be vital to evaluating whether or not a technology is mature enough to proceed to integration. The US Government Accountability Office, has stated that: *«Our best practices work has shown that a technology readiness level of 7— demonstration of a technology in a realistic environment—is the level of technology maturity that constitutes a low risk for starting a product development program."* (U.S. GAO, 1999). The TRL level therefore can be seen as a measure of the remaining risk that will be carried into the program or project. At the same time the US Department of Defense (DoD) have considered at TRL equal to or greater than level 6 to be a mature technology; ref (Conrow, 2009), the Science technology objective (STO), among other works on maturing technology until TRL 6 for further implementation in US. DoD programs (Graettinger, Garcia, Schenk, & Van Syckle, 2002), while DoD have agreed with GAO that a TRL 7 is preferable upon integration in programs already in 1999, yet this does not seem to be a requirement, even it if is a reasonable wish for the level of maturity for technology to be implemented.

Organizing delivery around TRL. There are many ways of assessing the risks by implementing the technology at a low TRL. Dacus found that risk evaluation may be completed by using squared TRL shortfall (eq. 2) to communicate the relation between the 'TRL shortfall at integration' and the 'severity of the additional risks by integrating immature technology' (Dacus, 2012). Dacus further presents the following equations where TRL_i is the TRL level of the technologies to be integrated;

weighted severity of issues $$SS = \sum_{i=1}^{N}(8 - TRL_i)^2 \quad \text{(eq.1)}$$

Maximum technical shortfall $$Max = Max(8 - TRL_i) \quad \text{(eq.2)}$$

The Dacus study further apply these equations to past projects, and show that with less than the recommended *3 maximum technology shortfalls* have a mean of 7,7 months' delay, with additional costs of 3,2 %, while the projects that violate this rule had a mean 31,2 months' delay and a 35,5 % cost overrun.

TRL Heterogeneity: In a study performed in 2011 two alternative sets of technologies with average TRL at μ_{TRL}=6 are presented for integration. (Dubos & Saleh, 2011) One shows heterogeneity of TRLs, while the other has a variable set of TRLs for the technology. The study concludes that a heterogenic TRL pool with all TRLs included equal to TRL 6, is clearly beneficial for the overall schedule risk, as compared to a variation of TRLs with similar average (Dubos & Saleh, 2011).

To try to understand this number better, it is aligned with the weighted TRL scale, presented by Conrow (Conrow, 2009). The TRL scale is an ordinal scale where each unit has a different inherent value. Conrow has used Analytic Hierarchy Process (AHP) to calculate from an ordinal to a cardinal scale, distributing the scale according to resource use. The results from Dubos have been reassessed below, to see to what degree the average TRL is in fact still an average. The TRL values of the Dubos arrays (pf_{1D} and pf_{2D}) were exchanged with the equivalents of Conrow (pf_{1C} and pf_{2C}, to see if the ordinality of the scale is the reason for the effect found in the study;

$$pf_{1D} = [6\ 6\ 6\ 6\ 6\ 6\,] \text{ and } \quad pf_{2D} = [4\ 5\ 5\ 7\ 7\ 8\,] \quad \text{where} \quad \overline{pf_{1D}} = \overline{pf_{2D}} = 6$$

The resulting arrays when converted to Conrows weighted TRL scale are

$$pf_{1C} = [2{,}74\ 2{,}74\ 2{,}74\ 2{,}74\ 2{,}74\ 2{,}74\,] \quad \text{and} \quad pf_{2C} = [1{,}14\ 1{,}97\ 1{,}97\ 4{,}26\ 4{,}26\ 6{,}81\,]$$

Averaged variance change from

$$\delta_{1D} = 0 \ \ and \ \ \delta_{2D} = 1{,}42 \ \text{ changed to } \ \delta_{1C} = 0 \ \ and \ \ \delta_{2C} = \ 0{,}56$$

Corrected for the weighted scale, the average of the distributions change as shown below

$$\overline{pf_{1C}} = 2{,}7 \quad \text{and} \quad \overline{pf_{2C}} = 3{,}4 \ \Rightarrow \ \overline{pf_{1C}} \neq \overline{pf_{2C}}$$

This indicates that the TRL-heterogeneous project; even with the overall higher degree of maturity (when corrected for ordinal scaling), still has a higher likelihood of schedule slippage. This can be shown together with the cardinal and the ordinal scale in Figure 1.

It has been pointed out that the ordinal and subjective characteristic makes the TRL scale and other similar scales unsuited as cornerstones in other mathematical evaluation methods such as for the SRL; by giving results that are "computationally accurate, but irrelevant" (Kujawski, 2013).

In 2014 a study resulting in a scalable ontology for small and medium sized research organizations was published (Steele, 2014); he describes different types of risks mapped in relation to each TRL, in addition to presenting a set of activities that can be applied in accordance with the severity of the risks, the TRLs can clearly be used to indicate the right focus of systems engineering in order to limit the risks that are found to be linked to the different TRLs.

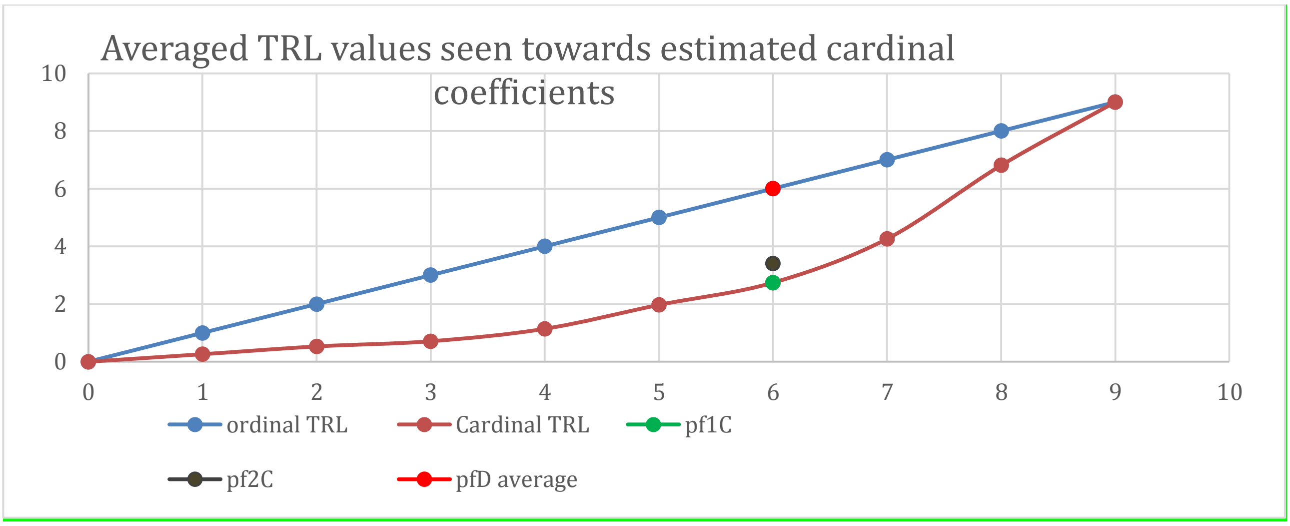

Figure 1 Graph indicating the equivalent TRL values based on AHP (Conrow, 2009) related to the averaged TRL of two arrays

TRL in a resource perspective The above described studies, to a large degree show that the risks indicated by the TRL level of CTE will affect the projects and programs. Additional cost overrun that comes with early integration should have a margin equal to the mean schedule slippage of the given TRL that will be integrated, since the delays can be anticipated upon early introduction into a program (Dubos, Saleh, & Braun, 2008). As an example, by the introduction of TRL 6 CTE into a system, a 30% margin should be adopted, referring to the Schedule Risk Curve in Figure 2. Specific industries may need to prepare equivalent graphs to be able to calculate the risk margin necessary to facilitate a high-risk project in their own industry.

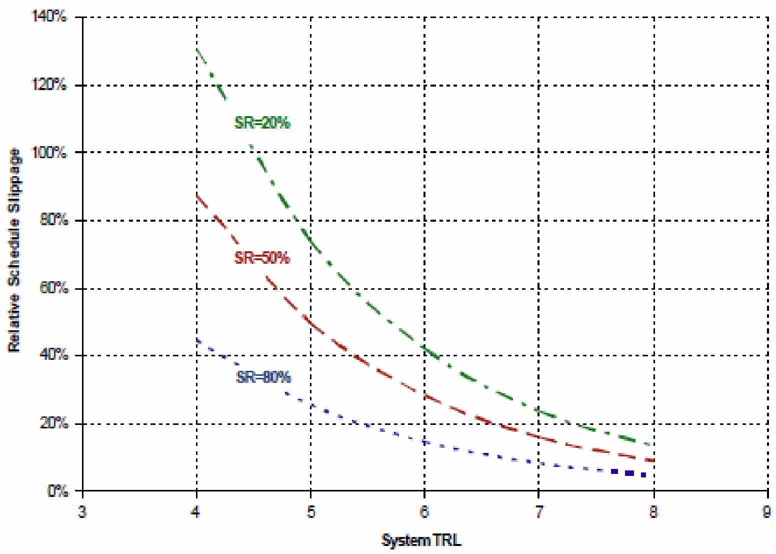

Figure 2 A copy of TRL Schedule risk curves (SR) for a normally distributed Relative Schedule Slippage defines the necessary margin to reduce schedule slippage risk (Dubos, Saleh, & Braun, 2008), based on numbers from (Lee & Thomas, 2001)

A general weakness of the TRL is that there is no way of knowing exactly how much resources will go into achieving one (more) TRL level. Hence the resources required for the next TRL transition should be reassessed on a periodical basis in order to evaluate the technologies likely applicability into systems that will be developed (Gatian, 2015). The recommended acceptance criteria from GAO, TRL 7, was found proven with an average 4,8% cost overrun with all technology matured, while immature technology provided an average 34,9 % cost overrun (Meier, 2008). (Katz, Sarkani, Mazzichi, & Conrow, 2015). It is apparent that TRL 7 is highly preferable as the (Katz, Sarkani, Mazzichi, & Conrow, 2015)shows that integration at TRL 6 show no significant relation to ‘no cost overruns’, which further indicates that the decision makers underestimate the cost of maturing technology from TRL 6 to 7. The relative schedule change (RSC) is clearly correlated to the relation between critical design review (CDR) to milestone C (MS C) in the US. DoD development process, indicating that a high Design Maturity at CDR is more relevant than the TRL in any case (Katz, Sarkani, Mazzichi, & Conrow, 2015). This study is the only TRL related literature I have found to indicate a more important metric than TRLs.

By defining the CTE for the project or program after the TRL scale, the maturity of an individual element may indicate possible failure of future mission unless sufficient degree of added funding or time is provided (Dubos, Saleh, & Braun, 2008). The TRL provides decision makers with information to take a well-founded decision on whether to stay with a low TRL-level technology with added funding and time, change to a more mature technology, or cancel the program or project. (Gatian, 2015). Most technologies integrated, are required delivered with a certain technical maturity. The TRL scale can provide value by pointing out the total risk reduction in the program, in the cases of early definition of critical components; these can be required at a higher TRL level at integration into the program as a mitigative effort, in order to effectuate a timelier delivery in accordance with the stakeholder requirements. To conclude the paragraph of TRLs effect on the projects, a reference to early integration such as with state-of-the-art hardware, with a maturity of less than TRL 4; validated in parallel with the program; is correlated to compromised mission success.” (Meier, 2008).

Suitability of use There is already a quite extended use of TRL through organizations such as; NATO (NATO, 2008), EU (EU, 2014), the US Department of Defense (U.S. DoD, 2010), the US Department of Energy (U.S. DOE, 2010), and US Homeland Security, subsea applications through API standard for subsea (Yasseri, 2016), (Yasseri, 2013), DNV-RP-A203 (DNV GL AS, 2017). Commercial companies like Boeing (Whelan, 2008), Google, Raytheon, John Deere, Alstom and BP (Olechowski, Eppinger, & Joglekar, 2015) are also using TRL. Challenges using TRL in different industries have to some extent been considered. The most relevant issues outside of the native domain is the lack suitable ways to consider system readiness, among other by the use of considering the lowest TRL as the weakest link. Moving a specific item from TRL 3 to TRL 5 may only require a few simple tests, the weakest link method does not actually reflect the remaining work or risk as degree of difficulty has not been not considered. BP has attempted to handle this by producing a TRL excel chart that also take degree of difficulty into account by color-coding. (Olechowski, Eppinger, & Joglekar, 2015).

The lack of alignment of TRLs with decision gateways has been mentioned when moving out of the Aerospace and Defense domain. Customizations as in the API N17 (Yasseri, 2013), that uses 7 levels; rather than 9; is an alternative. This however, also creates gaps to research; will the value that can be interpreted from TRL studies performed via NASA and DoD be valid when the scale changes? Google also indicated that the TRL is not suited for their operations and need to map the technology into future product roadmap, however the lack of a better alternative keeps the use of TRLs going (Olechowski, Eppinger, & Joglekar, 2015).

Upon achieving TRL 9_{NASA}, the equipment is expected to be military grade, this indicates that the product should have passed the infant mortality part of the bathtub curve. When turning to consumer markets, the risk of a few failed product units may be unimportant relative to the risk transferred to stakeholder upon actually ensuring that all equipment achieves TRL 9. The increasing risk of obsolescence may increase very fast, as for e.g. consumer electronics. This indicated that the levels of the TRL are not in line with other domains, where the main business value is not quality, but time or cost, where needs may go directly from an acceptable product (in accordance with defined requirements) to a need for a well-managed life-cycle, where failed products can be replaced fast and easily.

The above example indicates a need to customize the TRLs, which is happening to an extended degree. A following implication of the use of different TRL values, could in the long run cause complications to technology transfer between two entities cooperating cross-domain. Both entities may have a successful implementation of their own version of TRLs. The understanding of the TRL in the sociocultural production environment is not found mentioned. The different applications are rarely shown with a denominator identifying "original system", such as TRL_{NASA}, or TRL_{API}, or other, this could help avoid confusion. A relevant comparison is the use of SI and Imperial units. They normally do not meet within the same projects, yet somehow the confusion occurs and mistakes are made, this is human, and the best way to avoid it is to be specific.

In 2009, a survey was completed where technologists, developers and technology users were presented with the same set of data. The results showed a full 3 levels of difference partially based on perspectives – developers looked at the TRL scale from the documentation to provide proof of suitability. The understanding of relevant environment was pointed out as incongruent, as the developers tended to think that testing in real environments as too costly while program managers considered simulations to be too poor a representation. (Robinson, Levack, Rhodes, & Chen, 2009).

The idea of measuring maturity makes sense, however there is stark misunderstanding in the case where someone states this to be simple. How to define the TRL of a technology has been attempted specified several times (U.S. DoD, 2005), (U.S. GAO, 2009) (U.S. DoD, 2011), (U.S. DoE, 2011), the latest addition is the draft (U.S. GAO, 2016), which is in hearing until august 2017. In addition, tools such as the TRL calculator (Nolte, Kennedy, & Dziegiel, 2003) have been published, in an attempt to make the TRLs more available and unison. When applying TRLs it is imperative that the users are aware of the limitations of the system. Some of the limitations of the TRLs are specified throughout literature, a short list is presented here;

- *Integration and system views* are not included in the scope of the TRL, it is not possible to define whether integration interfaces are ready for integration to a top-level system. The system functions have not been considered, as they represent more than the sum of the parts, the simplified breakdown into individual technologies does not allow for this evaluation to be done. (Mankins J. C., 2002), (Sauser B. , Ramirez-Marquez, Verma, & Gove, 2006).
- *Capability*, which is the system's ability to produce an operational outcome is not considered in the TRLs (Tetlay & John, 2009).
- *Individuality of elements and their properties* Non-system technologies, such as processes, methods, algorithms, or architecture are not adequately considered (Graettinger, Garcia, Schenk, & Van Syckle, 2002).
- *Complexity and uncertainty* of an intelligent systems and their functions and assessments; measures cannot be assessed or controlled with TRLs. (Meystel, Albus, Messina, & Leedom, 2003)
- *Risk and degree of difficulty* are not assessed this gives no indication of the difficulty of transitioning to the next level. (Mankins J. C., 2009)
- *Continuously evolving systems* will not benefit from the NASA-TRLs, this is typical for software and introduced the need for 'TRL for non-developmental item (NDI) software'. (Smith, 2005).
- *Lifecycle aspects* are not considered in the transition to operation; TRL 9-NASA, does not give any further information about the systems expected life cycle (Straub, 2015).
- *Unorganized expansion of TRL***s** to adapt the system for consumer market R&D processes has been attempted (Straub, 2015) (Hicks, Larsson, Culley, & Larsson, 2009). Some, such as EU has also included at TRL 0 in some areas, but not in other areas (Schild, 2014).
- *Customization of TRL* - The use of TRLs in API N17 has been translated to follow the process of the governing bodies and development process (Yasseri, 2016). By harmonization with regulatory structures, the TRL scale is likely to provide value for all stakeholders involved.

- *TRL and development models* often don’t align. Stages gates (Cooper, 1996) have been proposed to contain or align with TRL transitions, in other cases the spiral model (Boehm, 1988) is applied, where each separate iteration represents a new TRL. TRL in combination with a rigid application of development processes has been identified to have a negative effect on high uncertainty projects. (Högman & Johannessen, 2010).
- *Obsolescence* causes lack of functionality relative to change of expectations as time passes. If a program progresses over decades, technology development will push a change in the requirements and technologies applied. The TRL has no way to indicate likeliness of obsolescence or the need for changes (Valerdi & Kohl, 2004).
- *Subjective judgement* – there has originally not been “one right way” to conclude the TRA. That indicates that the subjective opinion of the person doing the assessment may affect the outcome. Within this conclusion lies a person’s nominal understanding of the world and their inherent acceptance for risks, which may also affect the result. (Olechowski, Eppinger, & Joglekar, 2015), (Sarfaraz, Sauser, & Bauer, 2012).
- *Proliferation* of readiness parameters (SRL, IRL, Logistics readiness level, etc.) have occurred due to lack inclusion of consideration to complex systems, value chains, varying frameworks, human factors and other important metrics. (Tan, Ramirez-Marquez, & Sauser, 2011) (Nolte W. , 2011)

The limitations of the TRL scope has caused a wave of alternative readiness levels. There are many indicators that could point in the direction of success for a project; some of whom are: Manufacturing Readiness Levels (MRL) (Morgan, 2007), Integration Readiness Level (IRL) (Sauser, Long, Forbes, & McGrory, 2009), Design readiness level, Capability readiness level (Tetlay & John, 2009), Software Readiness level, Human readiness level, Logistics readiness level, Operational readiness level, Innovation readiness level (Lee, Chang, & Chien, 2011) and Programmatic readiness level as methods most commonly used according to U.S. Department of Energy (DOE) (Fernandez, J. A., Sandia National Laboratories, 2010).

In addition many qualitative assessments such as SRL (Sauser B. , Ramirez-Marquez, Verma, & Gove, 2006), TRRA, ITAM (Mankins J. C., 2002), TRL for non-developmental item (NDI) Software (Smith, 2005), TRL Schedule Risk Curve (Dubos, Saleh, & Braun, 2008) are based on a TRL evaluation in the core, therefore the relative importance of TRL increases as it has become a cornerstone to other evaluation systems. There exist other methods not based on TRL; yet the TRL scale remains an important scale due to the widespread use in governmental and multinational organizations such as the US governmental agencies, NATO and EU.

Content analysis

Throughout the multitude of documents describing the advantages and disadvantages of applying TRLs to new product development processes, the TRLs are often cited and described. In order to gain an understanding of what was the “right” TRLs or what degree of customization was applied an overview of the TRLs contents and descriptions was created. A sample of the summary tables is given in Table 1.

The remaining tables are presented in the Appendix A. The subsequent survey phrases were chosen based on the evaluations of how the different TRLs are communicated through academic and user organization literature. When looking through these tables, it appears that TRL 5 is the most diverse when described. TRL 6 that in many cases is just considered a more complicated version of TRL 5, is the least diverse.

Table 1 results from evaluation of description to TRL in different documents gathered from research papers and user organizations, mentioned at least 4 places.

The references used in the table below are shortened (coauthors left out) due to space restrictions,

they will be identified correctly in the appendix where the full tables will be presented. This is an example table.																		
descriptive words	Mankins 1995	Mankins 2002	Meystel 2003	Sauser 2006	Hicks 2009	Mankins 2009	Straub 2015	Nolte cal	NASA 2002	NASA 2012	GOA, 1999	DoD 2005	DoE 2008	DOE 2011	DOE CCSI 2012	NATO 2006	EU Horiz. 2014	Boeing 2008
validat*	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X
Component	X	X	X	X		X	X	X	X	X	X	X		X	X	X		X
relevant environment	X	X	X	X	X	X			X	X	X	X		X	X	X	X	X
test	X	X			X	X	X	X		X	X			X	X			
breadboard	X	X	X	X		X		X	X	X	X	X				X		X
Integrat*	X	X				X	X	X			X			X	X			
simulat* environment	X	X				X	X	X		X	X			X	X			
realistic	X	X	X			X	X	X							X			
demonstra*	X	X				X	X	X							X			
design							X	X							X			
interfac*						X	X	X							X			
high (-)fidelity								X			X			X	X			
Process								X					X		X			
component level	X	X				X	X											
subsystem level	X	X				X	X											
system level	X	X				X	X											

Survey results

A majority of the respondents were handpicked due to the field of work they do within new product development. Some responses were collected via the INCOSE website. The responses were distributed as shown in Figure 3. 56 % of the respondents answered that technical maturity was very relevant for work they do. The survey performed was intended to give a fresh viewpoint from project employees, valid for organizations where individual responsibility among the employees is emphasized.

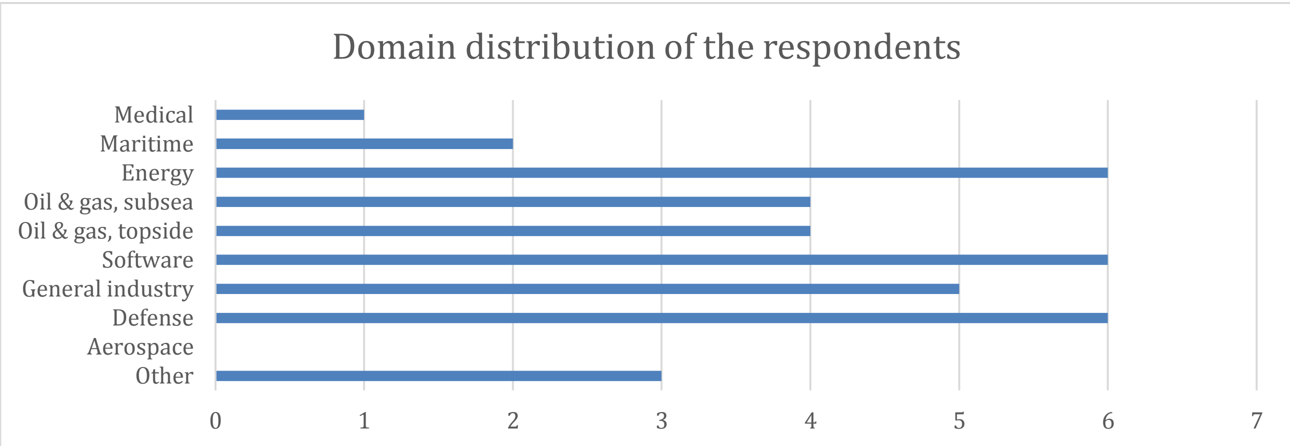

Figure 3 Distribution showing the domain of work of the respondents

The TRL documentation available is in a high degree based on defense or similar organizations, where the rank and responsibility is more set, relative to many smaller companies, where a higher number of people do more varied activities and share a more varied and possibly larger portion of the responsibility. Defense is also presented among the results, they do not deviate very much from the others in the survey, when it comes to responses, other than that they are very clear on the importance of technical maturity, by considering it far more important than the others. This could be due to the rigorously application of TRLs in space and weapon programs, throughout NATO, EU and, the US and Australia and others.

Typical statements found in literature that were rated Figure 4 **in are as follows:**
TRL 1: Initial scientific research and principles observed.
TRL 2: Speculative technology concept identified.
TRL 3-1: Critical functions defined.
TRL 3-2: Proof of concept
TRL 4-1: Laboratory demonstration of components.
TRL 4-2: Validation of elements that work together.
TRL 5-1: Component integration.
TRL 5-2: Testing in simulation of relevant environment.
TRL 6: A scale prototype demonstration.
TRL 7-1: Prototype demonstration in the operational environment.
TRL 7-2: High risk- and mission critical components evaluated
TRL 7-3: System/subsystem model demonstrations in order to assure management of project suitability.
TRL 8-2: Complete system qualified through testing.
TRL 8-3: DT&E (developmental test and evaluation) completed, system specifications met
TRL 9-1: Actual system used in successful mission.
TRL 9-2: TRL level does not include planned product improvements

	TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
TRL 1	57	-	4	13	13	9	-	-	4
TRL 2	39	17	4	-	35	4	-	-	-
TRL 3-1	-	22	30	-	9	13	9	13	4
TRL 3-2	9	22	17	13	13	9	13	4	-
TRL 4-1	-	9	22	35	4	17	4	4	4
TRL 4-2	4	4	9	26	17	22	13	4	-
TRL 5-1	-	4	-	26	26	13	26	-	4
TRL 5-2	-	-	9	13	9	22	22	17	9
TRL 6	4	-	9	4	26	39	13	4	-
TRL 7-1	4	-	4	4	26	17	22	17	4
TRL 7-2	4	9	17	17	22	17	9	-	4
TRL 7-3	-	4	22	30	17	17	-	4	4
TRL 8-2	-	-	-	9	13	4	30	30	13
TRL 8-3	-	-	4	13	17	30	30	4	-
TRL 9-1	-	-	4	-	9	9	-	30	48
TRL 9-2	13	4	4	4	13	4	13	4	39

Figure 4 The figure above is a heat map. Each row represents one "typical" statement – the numbers in the figure represents the percentage distribution for each single statement in accordance with the TRL scale. The items with the bold frame are the correct answer for each of the statements.

The heatmap in Figure 4 shows the higher percentage responses (above 25%) as green, between 25% and 13% as white, and below 13% as red. This is an often-used chart type when it is necessary to visualize large apparently unstructured datasets. The TRLs 1 and 9 are fairly simple to spot, and at most 57% for the responses were correct with regard to these, however after crossing TRL 4, the distribution is less centered, indicating some confusion concerning the 'intuitive' content of each individual TRL level. The most relevant part of this result is the variation around TRL 5-7. If a discussion is ongoing within a program, and a number of people are participating – it is unlikely that the participants are able to individually identify what a TRL 5, TRL 6, or TRL 7 actually means without further specification or discussions. Of the respondents, 13 work in R&D, engineering or design, while 8 work as project managers and 9 work as technical managers (a few of these were overlapping). These are all to some extent within the target group that the TRL system is created for as specified; "research personnel, research management and program management" (Sadin, Povinelli, & Rosen, 1989). Observing Figure 4, it appears that it is the levels TRL 5, TRL 6 and TRL 7 statements, are the most likely to be misinterpreted. This is unfortunate in parallel with the increasing importance of the individual TRL levels, as mentioned in the literature review.

Knowledge of TRL The respondents in the survey have stated their knowledge of TRL levels. The median value is 2, while the average is 2,7. The scale ranged from 1 to 5, where no 1 is 'no knowledge' and 5 is 'experienced user'. This indicates that quite a few are completely new to the TRL scale, while others have used it somewhat before. This information reflected onto the heatmap above, indicate that the TRL levels are not very intuitive, and at a minimum need context to make sense.

Resource distribution over the TRL scale The respondents in the survey were asked to define which TRL step they considered to be the most expensive, while being able to read what each of the TRL steps contains. In Figure 5 there is a presentation of the survey result towards the results of the actual cost variation from the (Conrow, 2009) study. On a distribution level, the respondents are quite close to the actual cost distribution, the levels do increase in cost as the maturity increases. The number of respondents is too low to say accurately, but at least it is clear that the respondents understand that there will be clear differences in costs of TRL levels. No respondents answered that the costs were equally distributed.

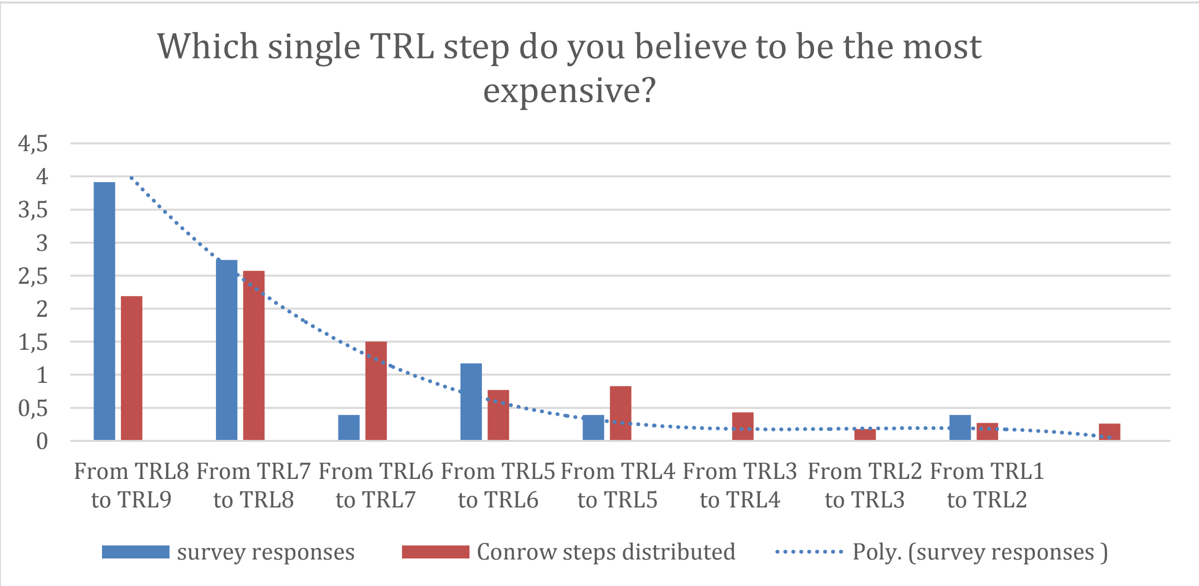

Figure 5 cost per TRL, comparing survey responses realtive to the cardinal distribuiton based on (Conrow, 2009)

After completing the initial statements estimation and cost estimation of the survey, some questions regarding the possible use of maturity metrics was asked. In Figure 6 the most important and conclusive considerations of the respondent's opinions are collated. It is evident that the respondents think that technology maturity is a useful measure, however there can be raised questions with regards to why it is not commonly used.

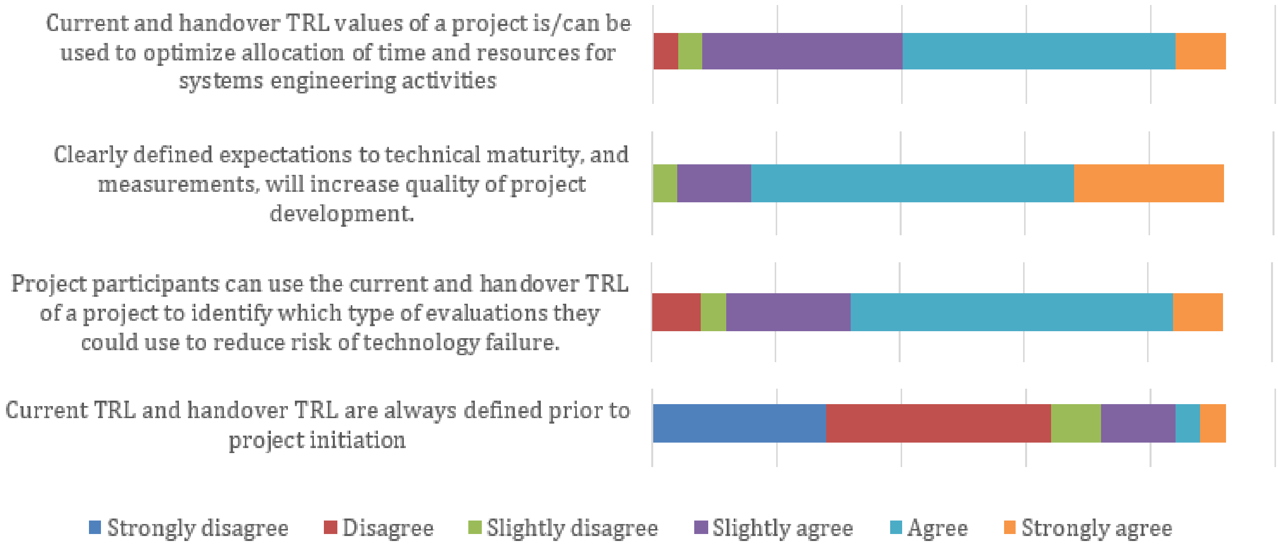

Figure 6 Question from questionnaire on a rating from 1-6

Discussion

The discussion begins with an evaluation of the results as they address the research questions.

TRL can be stated in requirements, does this drive the need for systems engineering?

When the TRL for the end product is stated as a requirement from stakeholders it generates a need to validate that the level has been reached. The requirement sets a clear expectation to the functional level of the end product. Meier specifies that investments in Systems Engineering is vital to avoid future cost slippages; and concludes that: "Systems engineering serves as the glue that binds the technical solution to the high-level requirements and maintains the program baseline." The results of his study show that "inadequate systems engineering, coupled with a broken requirements process and immature technology, inevitably leads to program failure». (Meier, 2008) Evidence that the need for systems engineering is related to the use of TRLs in literature cannot be found in literature. If TRL is stated as a requirement, the needed level for verification or validation of this TRL should be reflected in the wording of the other high level requirements. This indicates a need for thoroughly defined requirements to ensure that the TRL requirement and the functional requirements go along the same lines and do not contradict or over specify relative to the achievements required in the TRL. Systems engineering becomes relevant in the cross section where complexity meets a need for reliable plans and outcome quality (Honour, 2004). The readiness level transitions in a project could therefore give an indication of what types of systems engineering tools to use and what risks these should limit, even if several other factors are can be seen as equally or more important for systems engineering application depending on the individual projects specification.

TRL can be used to determine risk in the program, does this drive the need for systems engineering?

At the start of any project a definite set of uncertainties exist, this indicates that a project has an initial set of risks, whether these are defined or not. The risks that are not defined and mitigated or otherwise dealt with are accepted when steering the project after a cone of uncertainty (Boehm, 1988) or other suited practices. The TRLs will not in any way change the initial risks of the project, other than that the handover TRL will indicate delivery expectations with regard to stability and to some extent the function of the product. The project management will use the TRL as a part of the feedback loop; when assessing whether the project is on the right track. By evaluating the TRL, this may be used for decision-making where a higher degree of systems engineering may be required in order to limit uncertainty or reduce risks. If the project is following the expected route and the risk is considered under control, no additional incentives will be necessary. Therefore, the TRL cannot be seen as a driver for systems engineering, however it can be seen as a way of pointing out the need to make adjustments, if the overall risk upon receiving the TRL information of CTEs appear to be higher than acceptable.

The respondents were asked questions about the relation between risk mitigation, systems engineering and TRLs; the results show that there is in fact a high degree of confidence that maturity metrics can provide valuable information on how to handle the project risks. Systems engineering offers a "technical framework for conducting trades among systems performance, risk, cost and schedule" (Reed, 2009). TRLs can be seen as metric measurement in the feedback loop that guides the continued systems engineering process, by including this view, value engineering is implemented into the systems engineering process. Value engineering is a field of engineering that systematically evaluates functions of systems, equipment, facilities, services and supplies for the purpose of achieving the lowest life -cycle cost consistent with required performance reliability, quality and safety" (Mandelbaum & Reed, 2006). The intention should be to provide well defined, quantitative check points for management to respond in a short time. This would integrate business objectives into the end-to-end development process, as is described as general needs of product development processes in (Holmes & Campbell, 2004).

TRL often affects determination of budget and schedule parameter, does this drive the need for systems engineering?

In order to be able to consider the value of SE in specific projects, it has to be considered that not all projects have the same end point. At a target company, some projects deliver documentation equivalent to a technical maturity TRL 2 while other projects deliver a TRL 6 or a TRL 9 systems. The percentage of resources invested in SE should logically in these cases be different, as an early phase project is likely to need a considerable higher percentage of SE than a later phase project under ideal conditions. The TRLs have also been used to indicate the real value of possible investments (Shishko, Ebbeler, & Fox, 2004). By using the TRL to evaluate the value of a project, there are clear expectations with regard to an effective management of the projects; however this is not addressed in the referenced article. Regardless of TRL, the value of systems engineering has been considered by the percentage of the resources applied towards the end cost and schedule for projects. The conclusion shows that systems engineering decreases cost and schedule overruns, as presented in Figure 7, (Honour, 2004).

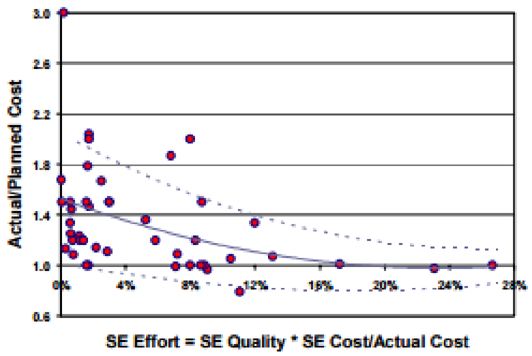

Figure 14. Cost performance as a function of SE effort

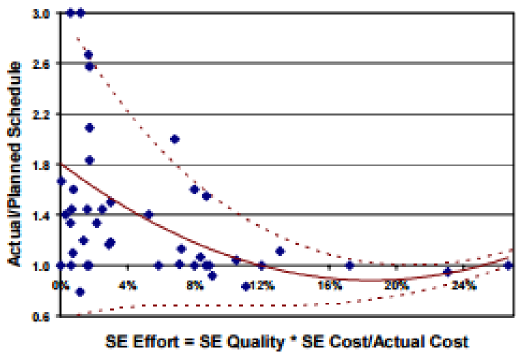

Figure 15. Schedule performance as a function of SE effort.

Figure 7 Graphs show the results from study by Eric Honour through INCOSE (Honour, 2004)

The optimum SE effort to be 15-20% of the project, however it is noted that the data specifies normal budgets to be along 3-8% (Honour, 2004). The value of Systems engineering is therefore considered proven, however the correlation between value of systems engineering and the TRL level at which the products are delivered is unexplored, it may vary greatly with the project type and degree of difficulty and (to my knowledge) is not yet found to be proven.

(Meier, 2008) has conducted research on behalf of different US government agencies and concludes with a need to invest in systems engineering. The conclusion does not as much point to technical maturity at acquisition as the main culprit even if it is held up as a contributing factor. Meier specifies requirement creep to be the largest single factor to effect end results. Some of the problems of pointing towards the need for investment in systems engineering is the expansive definition of the discipline itself, the Systems engineer performs several roles in a project, contributing with project management tools, through requirements ownership, systems design, systems analysis, validation and verification, logistics, glue among subsystems, interface, technical managers, etc. (Sheard, 1996). It is possible to spend too much effort in one area, while neglecting another. Systems engineering is a technical discipline, however differing from electrical and mechanical and other engineering disciplines; the lack of a physical end product makes the value of systems engineering difficult to quantify (Valerdi R. , 2005). Based on Meiers conclusion there is an apparent need to increase general spending on requirements ownership, however the other roles are not specifically identified within the documentation. Yet with a broken requirement, it may be difficult to design the right system and validate the correct system function. This indicates a substantial degree of dependence between the different systems engineering roles. In turn the effect of systems engineering spending will have a cascading effect from the start of the project. The correct spending at the right TRL level as an indicator could help by ensuring that the start of the project is handled sufficiently well; ensuring a good basis for the other systems engineering roles to be able to do their jobs. It could be that this kind of evaluations could be related to the Steeles scalable ontology (Steele, 2014), where combining project details in a database could give an indication of optimal spending within the organization over time.

How does this information affect other industries?

In automotive, and to some extent also in general industry, the lean approach is more common than in typical systems engineering businesses (Welo & Ringen, 2015). When responsibility for improvements trickles down to the employees; as is normal in lean companies; the need to understand the global view increases. The survey responses retrieved include the evaluation of 18 statements from the TRL tables that were typical descriptors for TRL levels.

If there is such a thing as a possible way to consistently understand and apply a maturity metric, this will likely improve the results. Checking a 1 digit number is possible to do for any project employee, sales representative or other; especially if this employee is aware that they may be saving the company of an average higher than 30% (Meier, 2008) cost overrun. The insecurity may however lie in the performance of the TRA. The functions of the TRLs are to ensure that a communicated level of maturity has been reached. A successful level of communication around TRL requires that all parties have the same understanding of what a TRL level entails.

Recommendations for future work

Maturity metric standardization - It is apparent that the response to the above title; is that TRL is already defined in a set manner. The TRLs likely serve as a beta-test for a tool that is suitable for all domains with varying degrees of complexity. It may be that the best evaluation method can be found one metalevel up, and defines a set of evaluations that is applicable to different systems, times, places, organizations and that would give the relative end level that was relevant to any specific product. The ideal solution would be a modular solution, where the different layers of evaluation was chosen based on the specification of the product.

Development of definitions of TRL over time would have been included in this work if there was more time. A TRL level in its semantic cloak is not necessarily the same today, as it was in 1995. By gathering more user organizations data, among other going into organizations that are users of the system to query about what they look for; and compare it towards the definitions from literature. There is a continuous development both of work methods, tools, and technology, and society. The past 10 years there has been an emergence of platform structures in society, where rather than a top down organization, people work in flat organizations. The tools and structures humans work with and under affect the way work is done, but when society changes, so must the ways people work change in order to stay relevant. The TRL scale is a great tool, but it may not be the best tool when responsibility is distributed at lower levels of the organizations.

The human aspect in an organization - Under the technical literature that is overarching the TRL concept, there appears to be one wall missing. The cultural human aspect of the use of TRL, not only with regard to regional culture, but also to the organization culture.

Lean organizations and TRLs The lean businesses process provide a lot of benefits. It could be valuable to consider whether the lean businesses get an impact of TRLs, or whether they are gaining the equivalent advantage through other methods. If this is the case, then the knowledge of which methods and what indicators to use for each specific project could come as a valuable contribution to research and development.

Conclusion

Based on the results presented in Table 1 the understanding of each individual technology readiness level varies, and is not conclusive without a context and a commonly agreed viewpoint. The TRLs are not intuitive, and prohibit clear communication regarding technology maturity when they are presented without reasoning, discussion, or context. A clear recommendation could be to always go through the definitions in discussions of TRL levels. An alternative is to keep a poster of the relevant TRL scale by the coffee machine/ water boiler or other effective means of visualizing the content for the personnel to which it is relevant, as a way of internalizing the scale and promoting discussions.

Specification of reference scale so that context is always maintained could be recommended as a standard, exemplified by e.g. $TRL7_{NATO}$ and $TRL7_{API\ 17N}$. The TRLs are not guaranteed to be equivalent to each other and this customization may ultimately cause confusion when creating cross domain complex systems or through transfer of technology. Transfer of technology is stated to be a highly-prioritized activity among both NASA and ESA. If technology is to be transferred, then for the receiving party to understand the level of maturity is essential for the future success of the project.

Even if the TRLs are weak in specificity and can easily be misunderstood; technology readiness levels can provide a suitable frame, indicating what risks are most likely at which TRL level; this can further be used to identify which systems engineering tools are most suitable after defining the specific risk profile in a given project.

The application of TRLs in lean organizations may require other strategies than what TRLs were originally intended to cover. The TRL was created for management and R&D to communicate between each other's and acquisition responsible. In a lean organization, where responsibility is seething down through the organization the need for the employee to see the bigger picture is greater. The resources and knowledge needed to perform a TRA indicates that it may be a less suited metric in the lean organizations. It is likely that the TRA works better in more hierarchical organizations, as it may not require as many persons to get involved in the TRA. Likewise the benefits that the typical systems engineering businesses gain from the TRL, may be gained through other process improvements in lean product development.

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Appendices

Appendix A

Content analysis TRL 1

Content analysis TRL 2

Content analysis TRL 3

Content analysis TRL 4

Content analysis TRL 5

Content analysis TRL 6

Content analysis TRL 7

Content analysis TRL 8

Content analysis TRL 9

Appendix B

The survey responses.

Appendix A

The results presented in the following pages are all stated as per the below citation list. It was found that these were a representative number of definitions. The two Yasseri references are based on the 7 TRL scale of API N17, and were excluded for the basis of the survey. Steele also to some extent diverges from the normal TRLs when looking at how these have been used in the results, even if his definitions originally are the same as NASAs. It has been decided to keep these in the appendix as they do provide interesting comments to the evolution of TRLs.

In some cases words are completed by a wildcard (*). That indicates that the word has been accepted with different endings as the same word, e.g. Demonstrate and demonstration.

Literature list for appendix A tables

1. (Mankins J. C., 1995)
2. (Mankins J. C., 2002)
3. (Meystel, Albus, Messina, & Leedom, 2003)
4. (Sauser B. , Ramirez-Marquez, Verma, & Gove, 2006)
5. (Hicks, Larsson, Culley, & Larsson, 2009)
6. (Mankins J. C., 2009)
7. (Yasseri, 2013)
8. (Steele, 2014)
9. (Straub, 2015)
10. (Yasseri, 2013)
11. (Nolte, Kennedy, & Dziegiel, 2003) details from the calculator included
12. (NASA, 2012)
13. (U.S. DoD, 2005)
14. (U.S. DoD, 2009)
15. (U.S. GAO, 1999)
16. (U.S. DoE, 2011)
17. DOE CCSI 2012
18. NATO 2006*
19. (EU, 2014)
20. (Vegvesenet (NPRA), 2016)
21. Boeing: (Whelan, 2008)

Technology readiness level 1

Table A 1

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
principle	X	X	X	X	X	X		X	X		X		X		X		X	X	X	X	X
observed/observation	X	X	X	X		X		X	X		X		X		X	X	X	X	X		X
report	X	X	X	X		X		X	X		X		X		X	X	X	X			X
Basic	X	X	X	X		X		X	X		X		X		X	X	X	X	X		X
research	X	X			X	X	X	X	X		X	X			X	X					
scientific	X	X				X		X	X		X	X			X	X	X				
applied	X	X				X		X					X		X	X					
development	X	X				X	X	X	X			X			X		X				
translate	X	X				X		X				X			X	X					
lowest level	X	X				X		X	X						X	X					
properties	X	X			X	X										X					
technology maturation	X	X				X															
initial								X			X										

Technology readiness level 2

Table A 2

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Formula*	X	X	X	X		X		X	X			X	X	X		X	X		X	X	X
Applica*	X	X	X	X	X			X	X			X	X						X	X	X
Concept	X	X	X	X	X			X	X	X			X						X	X	X
Basic	X	X				X		X			X	X		X	X		X	X	X		
technology	X	X		X	X			X	X				X						X	X	X
practical	X	X				X		X						X	X	X			X		
speculative	X	X				X		X						X	X	X			X		
Invent*	X	X			X	X		X						X	X	X					
Design			X				X	X			X			X		X	X				
detailed analysis	X	X				X		X						X	X	X					
Defin*	X	X				X					X			X						X	
Observ*	X	X				X								X	X	X					
experimental proof	X	X				X	X												X		
Identif*	X	X				X					X						X				
analytic studies								X						X	X	X					
physical principles	X	X				X					X										
applied research				X	X											X					
characteristics	X	X				X															

Defin* is ambiguous and is used for define/defined/definition

Technology readiness level 3

Table A 3

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Proof-of-concept	X	X	X	X	X	X		X	X			X	X	X	X	X	X	X	X		X
Analytic	X	X		X	X	X		X	X		X	X	X	X	X	X	X	X			X
experimental	X	X	X	X		X		X	X				X	X	X	X	X	X	X		X
critical function	X	X		X	X	X		X	X				X	X	X	X	X	X			X
laboratory(-based) studies	X	X			X	X		X				X	X		X	X	X				
analytical studies	X	X			X	X		X			X		X			X	X				
prediction	X	X			X	X		X	X		X	X	X		X	X	X				
validation of application/concept	X	X			X	X		X			X		X		X	X	X			X	
research	X	X			X	X		X				X	X			X	X				
physically validate	X	X			X	X		X					X			X					
research & development	X	X			X	X						X				X					
design							X	X				X					X		X		
concepts formulated	X	X				X			X												

Technology readiness level 4

Table A 4

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Laboratory	X	X	X	X	X	X		X	X		X		X	X	X	X	X	X	X		X
Validat*	X	X	X	X	X	X		X	X				X	X	X	X	X	X	X	X	X
Component	X	X	X	X		X		X			X	X	X	X	X	X	X	X		X	X
System	X	X	X			X	X	X	X	X	X		X		X	X	X				
Breadboard	X	X	X	X		X		X	X				X	X				X			X
Low-fidelity	X	X			X	X		X	X		X		X		X	X	X				
Integrat*	X	X				X		X	X		X		X		X	X	X				
Requirements	X	X			X	X	X	X	X		X						X				
Test	X	X				X	X			X		X				X	X			X	
Demonstrat*	X	X				X	X	X	X		X				X		X				
Performance	X	X	X			X	X		X						X	X	X				
Work together	X	X				X			X		X		X		X	X					
Simulat*	X	X				X	X				X	X					X				
Concept-enabling	X	X				X			X												
Scale							X				X					X	X				
Prototype							X					X			X		X				
Bench-top	X	X				X															
Element (-s)	X	X				X															

Technology readiness level 5

Table A 5

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Validat*	X	X	X	X	X	X		X	X		X		X	X	X	X	X	X	X	X	X
Component	X	X	X	X		X		X		X		X		X	X	X	X		X	X	X
Relevant environment	X	X	X	X	X	X		X						X	X	X	X		X	X	X
Test	X	X			X	X	X	X		X	X	X		X	X		X		X	X	
Breadboard	X	X	X	X		X		X				X		X	X	X	X				X
Integrat*	X	X				X	X	X		X		X			X		X		X	X	
Simulat* environment	X	X				X		X		X		X		X	X		X		X	X	
Realistic	X	X	X			X		X		X		X					X			X	
Demonstra*	X	X				X		X		X		X					X			X	
Design							X	X		X		X					X			X	
Interfac*						X				X	X	X					X			X	
High fidelity/high-fidelity												X			X		X		X	X	
Process												X					X			X	
Component level	X	X				X				X											
Subsystem level	X	X				X				X											
System level	X	X				X				X											
Functio*							X					X					X			X	
Prototype							X			X							X				
Interfaces										X		X					X				
Preliminary										X		X					X				

Technology readiness level 6

Table A 6

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Prototype	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X			
Demonstra*	X	X	X	X	X	X		X	X		X		X	X	X	X	X	X	X		X
Relevant environment	X	X	X	X	X	X		X	X				X	X	X	X	X		X		X
Model	X	X	X	X		X		X	X			X	X	X	X	X		X			X
Test	X	X				X	X	X	X	X	X	X	X		X	X	X				
Integrat	X	X				X	X	X	X		X						X				
Representative	X	X				X			X		X		X								
Configuration								X			X				X		X				
Assuring management	X	X				X															
Scale	X	X				X															
Validation									X		X					X					

Technology readiness level 7

Table A 7

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Prototype	X	X	X	X	X	X			X		X	X	X	X	X	X	X		X		X
Demonstra*	X	X	X	X	X	X	X		X		X	X	X		X	X		X	X		X
Operational environment (or space environment)	X	X				X					X	X	X	X	X		X	X	X		X
Operational system	X	X				X			X				X		X						
Space environment	X	X				X			X			X									X
Scale	X	X				X			X		X						X				
Validat*								X	X		X				X		X				
Relevant environment				X	X											X					
Test									X		X		X		X		X				
Test bed aircraft									X		X		X								
Mission ciritical	X	X				X															
High risk	X	X				X															

Technology readiness level 8

Table A 8

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Qualified	X	X	X	X	X	X	-		X	-	X	X	X	X	X	X	X	X	X		X
System complete	X	X	X	X	X	X	-			-			X	X	X	X		X	X		X
Complete	X	X	X	X	X	X	-			-	X		X	X	X	X	X	X			X
End of true system development	X	X				X	-		X	-			X		X	X					
Qualified through test			X	X			-			-	X		X		X	X	X				
DT&E	X	X				X	-			-	X				X		X				
Flight qualified	X	X				X	-			-		X		X				X			X
Final form							-		X	-			X		X	X	X				
Configuration control							-	X		-	X						X				
Fit							-			-	X				X		X				

Technology readiness level 9

Table A 9

Description	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Actual system	X	X	X	X		X					X	X	X	X	X	X		X	X		X
Successful mission	X	X	X	X		X					X	X	X	X	X			X			X
Operational	X	X	X	X		X			X				X		X		X		X		
Realistic mission conditions									X				X		X	X					
Bug fixing	X	X				X			X												
Does not include planned product improvement	X	X				X			X												
Final form									X				X		X						

Appendix B

Responses to questions in survey

Some of the questions that were asked in the survey were not used in the final thesis. The responses were nonetheless interesting;

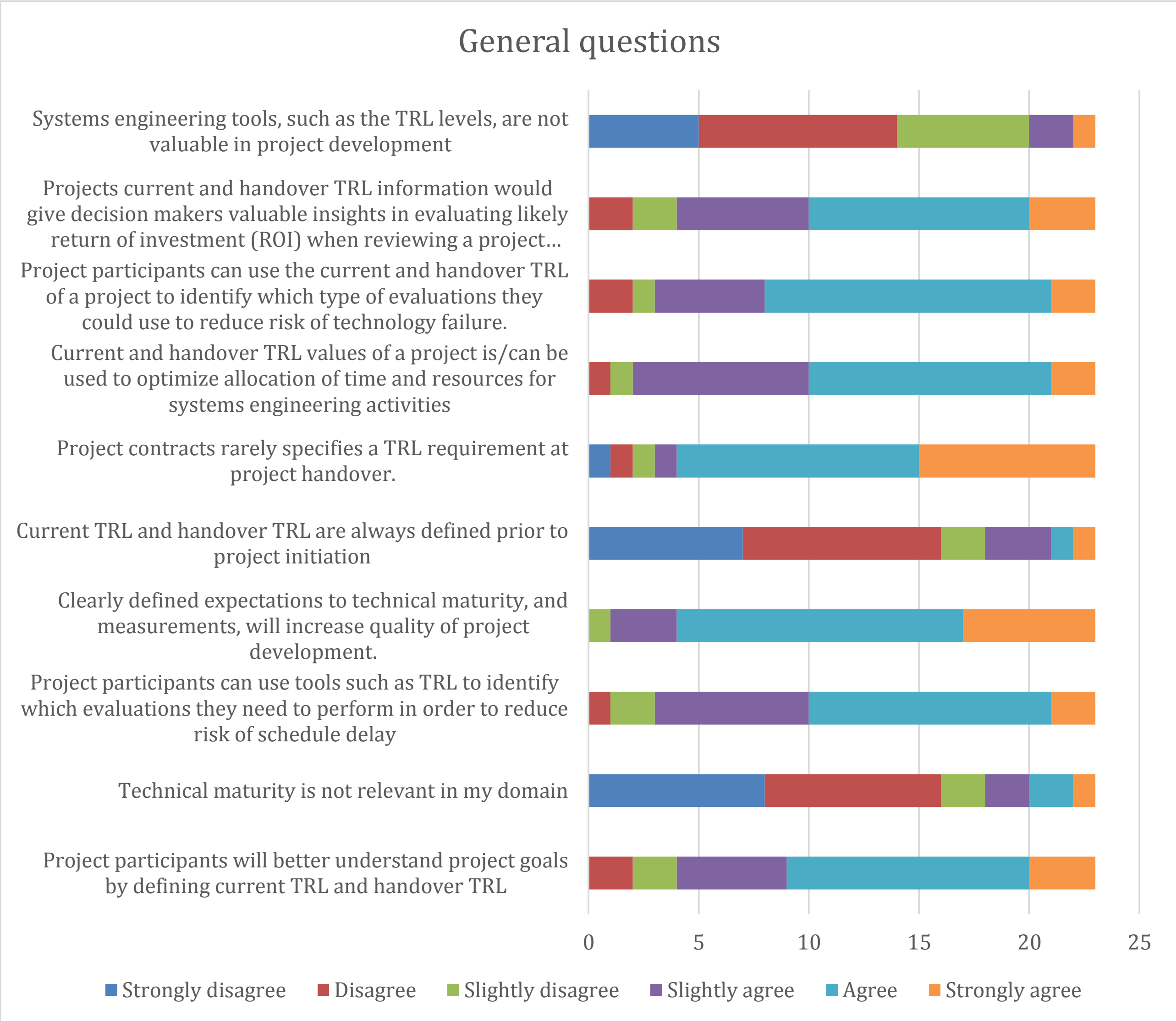

Figure B 1 Survey responses