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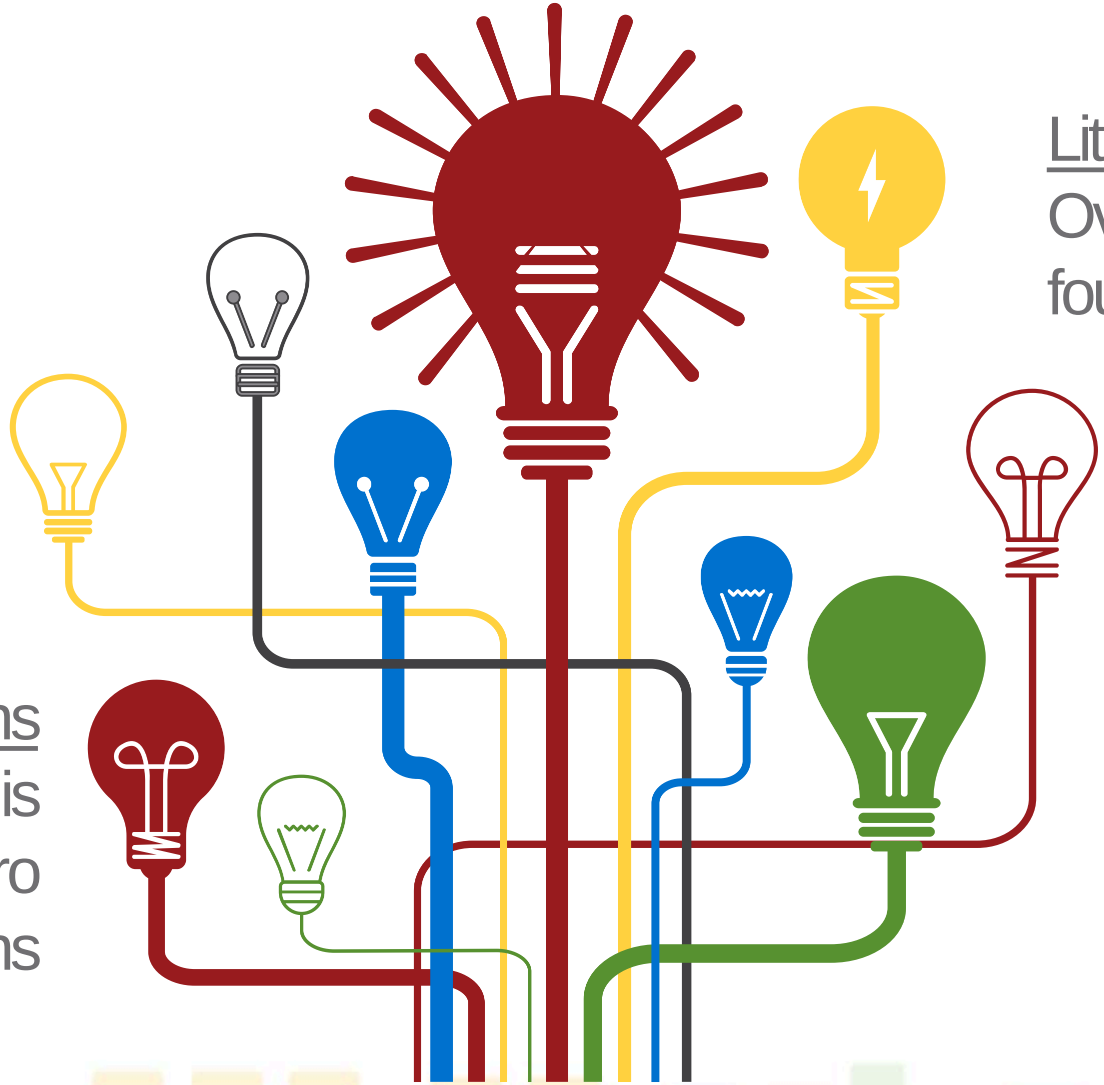
Kjersti Bakke and Cecilia Haskins, University SE Norway

Use of TRL in the systems engineering toolbox

Research Methods



Survey
Perceptions of TRL in industry

Limitations
The bulk of literature is from Mil-Aero applications

Literature Review
Over 50 articles found and analyzed

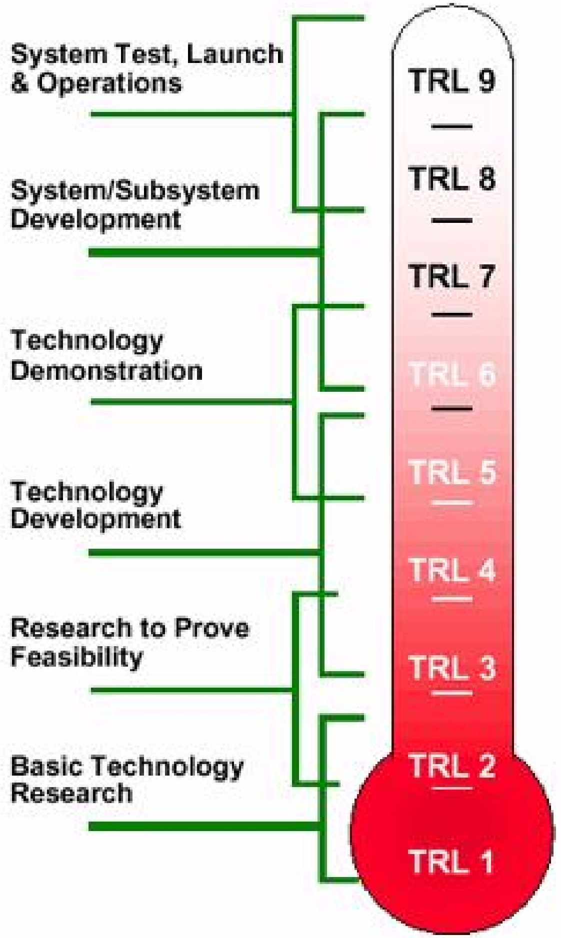
Context Analysis
Compare and contrast the various descriptions of the levels and how they can be used and assessed

Shrouded in mystery, what is it really, how can it assist systems engineering?

Technology Readiness Level

How TRLs are often portrayed

- The TRL levels are often visualized as a thermometer
- The red in the bottom indicate immature technology, and as the technology develops it matures
- Maturing can be achieved many ways;
  - Modify
  - Mitigate or
  - Qualify



Readiness or Maturity?

- Maturity is a scale
- Readiness is something you achieve when the function is adequately developed
- Literature uses these phrases interchangeably

- Consensus agrees that the TRL scale measures maturity

Background – designates maturity

1974
Stan Sadin, NASA
TRL 1-7
Invented

1989
Mankin
TRL 8-9
Expanded

2009
Straub
Hicks, et al.
TRL 10-11
Commercial application

2004
Valerdi & Kohl
Applied to Risk
Acceptance

2017
Austin, et al.
Bayesian networks
Validated

Progess and assumptions

- Defined delivery quality as a product of cost and schedule
- Originally created to achieve a “mutual agreement between research personnel, research management, and mission flight program managers” by differentiating technology maturity in a disciplined independent way
- The 9 levels version is the currently prevalent model
- An additional 10th and 11th level have been recommended in order to make the technology readiness assessment (TRA) commercially available
- Most recently, Austin et al. (2017) described application of Bayesian networks to the TRA

Suitability

- The TRL scale is used as an indicator of the embedded technical risk of a project based on the maturity of one or more critical elements
- However, due to the limitations of the measurement scale, several factors that also influence risk are not a part of the TRA
- Nonetheless, TRLs remain a part of basis for decision making in projects and programs
  - Why and how does it work?
  - How do people understand a maturity measurement?
  - Under what conditions is it used or not used?
  - From a systems engineering viewpoint, how does it affect the way people work within projects?

Limitations - 1

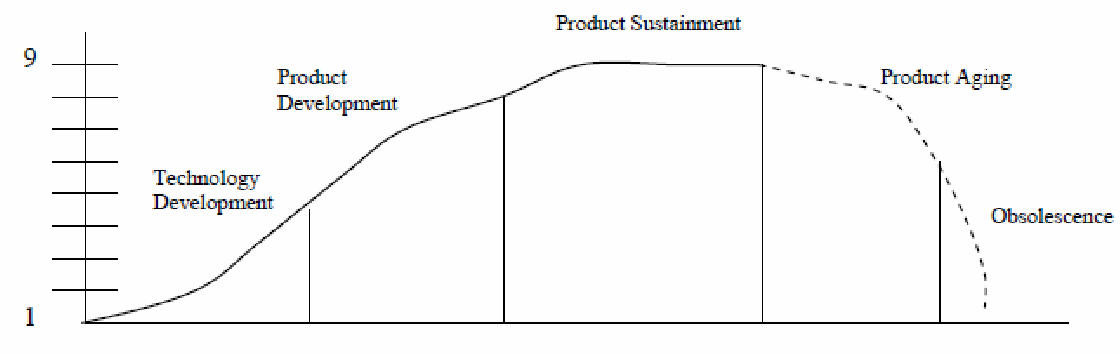
- The original application of TRL was for the assessment of a single technology development. Many complex projects involve multiple technologies, e.g., integration interfaces, lifecycle considerations and non-system aspects such as methods, algorithms, or architecture.

- TRL is a snapshot. It tells maturity of a technology at a point in time, but many other factors are to be considered when deciding to insert a technology in a program.

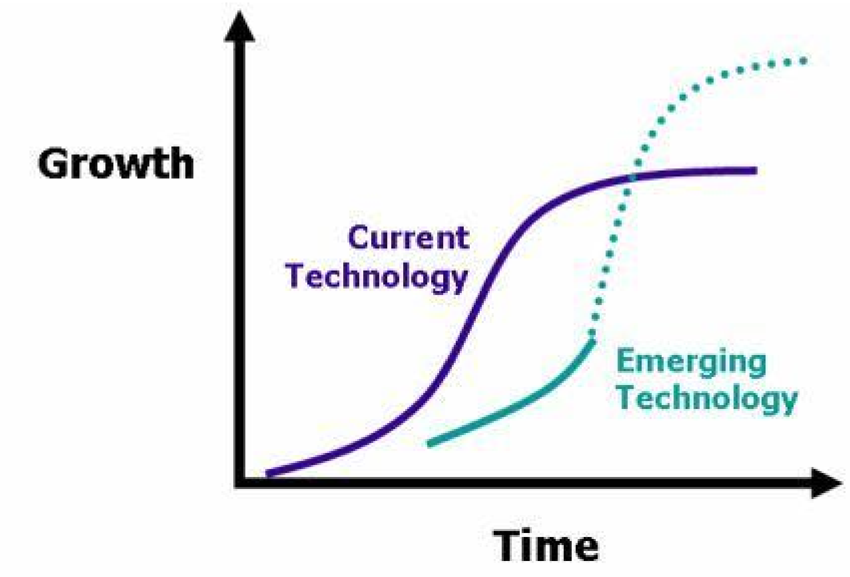
- Technology readiness is a measure of the maturity of that technology for use in a specific application. Therefore the same technology may be mature in one context and immature in another.

Limitations - 2

- Obsolescence occurs in nearly all technologies and yet the TRL model does not provide for any acknowledgment of this ‘retiring’ factor for a given technology. Pushing a product up the TRL ladder increases risk of obsolescence.



- Another major factor as to why a given ‘high TRL’ technology could loose some of its appeal is the emergence of a new but even better technology that provides nearly equivalent capabilities. This ‘leap-frogging’ effect is not addressed in the TRL model.



Limitations - 3

- The TRA process contains a significant level of subjectivity due to the employment of subject matter experts, and their interpretation of a critical technology's compliance in achieving a specific level definition

- The TRL scale does not estimate risk. Therefore, TRL methodology is not integrated well with cost and risk models.

- Interpretation of TRL definitions is typically not performed in a standardized or formal manner. TRL definitions provide latitude for broad interpretation.

Limitations of TRL – non-technical aspects

Effect of limitations

- Unorganized expansions through additional levels that may add new content to the existing scale to fit other industries or business drivers

Results of limitations

- Customization of TRL to fit development process or governmental acceptance process
- Proliferation through creation of a number of other evaluation readiness levels

‘Readiness Level’ proliferation

- ***Proliferation*** of readiness parameters have emerged to include considerations for complex systems, value chains, varying frameworks, human factors and other important metrics (Nolte, 2011)
- The limitations of the TRL scope has caused a proliferation of alternative readiness levels, of which the most frequently mentioned are:
  - Systems Readiness Level (SRL) (Sauser B. , et al., 2006)
  - Integration Readiness Level (IRL) (Sauser, et al., 2009)
  - Capability readiness level (Tetlay, et al., 2009)
  - Design readiness level
  - Software, Human, Logistics, and Operational readiness levels
  - Manufacturing Readiness Levels (MRL) (Morgan, 2007)
  - Innovation readiness level (Lee, et al., 2011)
  - Programmatic readiness level

TRL – cost to improve

- It is difficult to define the amount of resources required to achieve one increment of TRL transition.
- The expected cost of the next TRL transition should be reassessed on a periodical basis in order to evaluate the likely applicability of a technology insertion into a system under development (Gatian, 2015).
- TRL 7 is the recommended acceptance criteria from USA GAO, and was associated with an average 4,8% cost overrun with all technology matured; while less mature technology resulted in an average 34,9 % cost overrun (Meier, 2008; Katz, et al., 2015).
- Therefore, TRL 7 is highly preferred at integration, which may account for why decision makers tend to underestimate the cost of maturing technology from TRL 6 to TRL 7.

TRL - customization

- Commercial usage is driving a practice to customize TRLs
- A consequence of the use of customized TRL values is complications for technology transfer, or similar exchanges, between two entities cooperating cross-domain. Both entities may have a successful implementation of their own version of TRLs.
- The different applications are rarely shown with a denominator identifying “original system”, such as TRL_{NASA}, or TRL_{API}, but this could help avoid confusion.

Technology Readiness Scale (NASA)

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

https://www.nasa.gov/pdf/458490main_TRL_Definitions.pdf

Content analysis

- A review of the literature noted that TRLs are often cited and described, but rarely using the same language
- Content analysis was used to gain an understanding of what was the “right” TRL description or the degree of customization
- When looking through these tables, it appears that TRL 5 (shown in slide 19) is the most diverse.
- TRL 6, that in many cases is considered a more complicated version of TRL 5, is the least diverse.

The items included in the list are

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. (U.S. DOE, 2012)
18. NATO 2006*
19. (EU, 2014)
20. (Vegvesenet (NPRA), 2016)
21. Boeing: (Whelan, 2008)

Table 1 results from evaluation of description to TRL 5 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 problems, 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											

(Bakke, 2017)

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	X	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															

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															

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															

Content analysis findings

- It appears that the text and descriptions are to some extent similar
- Certain words are exchanged, which can skew the meaning
- Descriptive texts may have different lengths, this effects the level of detail of the definitions
- Some do not extend past one sentence. Others have long explanations, such as the TRLs described for U.S. DoD TRL handbook for Medical equipment (2009)
- All in all, TRLs are not 1 thing, they are more like variations over the same note, which may sound very differently.
- The subsequent survey phrases were chosen based on the different TRL definitions found in the academic and user organization literature.

Survey respondents

The survey was intended to give a fresh viewpoint from project employees who use TRL as part of their job

Other sectors

6%

40%

Energy Sector
Including Oil & Gas

Software Sector

17%

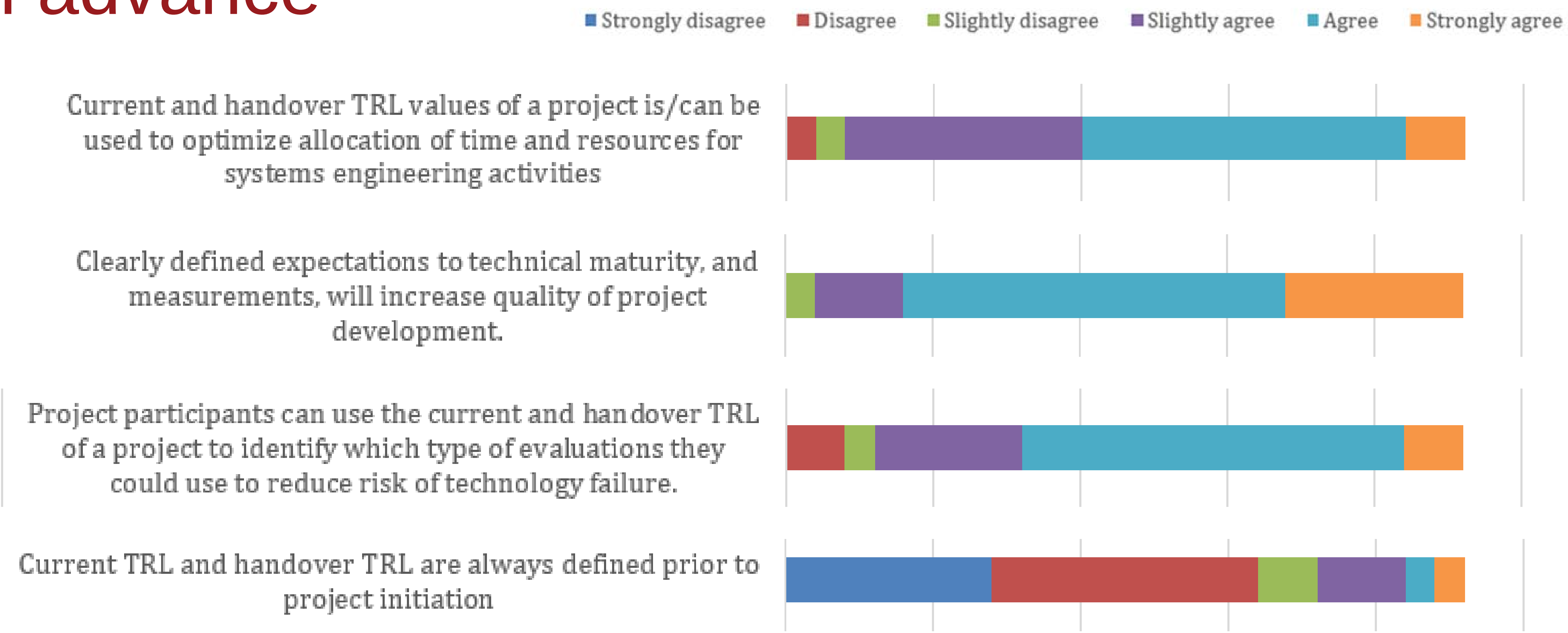
37%

Industrial Sector
Including defense and maritime industry

Survey of industry users of TRL

- The survey was composed of 18 statements that contained typical descriptors for TRL levels.
- The TRLs 1 and 9 are straightforward and received the greatest number (57%) of correct identifications.
- Above TRL 4, the distribution indicates some confusion concerning the content of each individual TRL level.
- It appears that it is around the levels TRL 5, TRL 6 and TRL 7 that statements are the most likely to be misinterpreted.
- The most relevant part of this result is the variation around TRL 5-7, i.e., if 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 is without further specification or discussions.

Respondents think that technology maturity is a useful measure, but TRL is rarely defined in advance



TRL in the SE toolbox

TRL as a requirement

Creates a need to validate that the level has been reached and the need to establish a technical performance monitoring plan

Maturity metric

Checking a single digit number as an indication of maturity is easy enough for any project employee, or other stakeholder

Project risk

Survey results show that there is a high degree of confidence that maturity metrics can provide valuable information on how to handle risks against a schedule

Communication

Successful communication around TRL requires that all parties have the same understanding of what each TRL level entails

Build Confidence

- Use of the levels shows a structured and managed approach and helps identify what will be required in later phases
- A clear verification path demystifies the novelty of a system, encourages innovation
- Evolutionary development process
- FAIL FAST, FAIL CHEAP .. Get out and test the key areas first

Thanks to Mullholand, 2017

WISUB PRODUCTS - TECHNOLOGY READINESS LEVEL (TRL)

Maelstrom and Torden products

The following TRL definitions are based on API (American Petroleum Institute) recommended practice.

Technology Readiness Level	WiSub Related Milestone
TRL 0 Unproven idea/proposal. Paper concept. No analysis or testing has been performed.	**October 2010:** Conceptualized, initial feasibility analysis of permeability of seawater to microwaves for data transfer through seawater
TRL 1 Concept demonstrated. Basic functionality demonstrated by analysis, reference to features shared with existing technology or through testing on individual subcomponents/subsystems. Shall show that the technology is likely to meet specified objectives with additional testing.	**December 2010:** testing of basic MW transceiver modules through seawater, and pressure testing of same modules in freshwater to 350 bar while under operation / communication. **February 2011:** Patent filed.
TRL 2 Concept validated. Concept design or novel features of design validated through model or small scale testing in laboratory environment. Shall show that the technology can meet specified acceptance criteria with additional testing.	**August 2011:** Tank testing of connector pair in seawater tank 
TRL 3 New technology tested. Prototype built and functionality demonstrated through testing over a limited range of operating conditions. These tests can be done on a scaled version if scalable.	**August 2012:** 100 Mbps prototype completed 
TRL 4 Technology qualified for first use. Full-scale prototype built and technology qualified through testing in intended environment, simulated or actual. The new hardware is now ready for first use.	**June 2013:** Clients begin lab and field testing of WiSub connectors integrated to their offshore/subsea equipment
TRL 5 Technology integration tested. Full-scale prototype built and integrated into intended operating system with full interface and functionality tests.	**December 2013:** WiSub connectors integrated to work-class "HD" ROV systems and operated offshore, Norwegian sector of North Sea and abroad, through ROV control system.
TRL 6 Technology installed. Full-scale prototype built and integrated into intended operating system with full interface and functionality test program in intended environment. The technology has shown acceptable performance and reliability over a period of time.	**January 2014 to present:** Testing is ongoing: on-shore, on internal near-shore test facilities, and on client equipment. BOP and ROV systems are primary installed platforms.
TRL 7 Proven technology. Technology is integrated into intended operating system. The technology has successfully operated with acceptable performance and reliability within the predefined criteria.	**January 2014 to present:** WiSub maintains strong client relationships and industrial partnerships that ensures Maelstrom and Torden product use and testing is ongoing, installed and operating on offshore/subsea systems.

Summary

- A high TRL is not a guarantee of success, but it is a way to reduce Technology Development Risk when applied to critical system elements.
- The use of TRLs (and associated metrics) require clear definitions and clear specifications of the required criteria to objectively determine each maturity level and additional SE tools to apply to a project.
- TRL values only measure technical maturity (or immaturity), but other factors affect cost growth and schedule slippage besides technical maturity. Thus, TRL values may not be highly correlated with risk, including schedule slippage.
- When TRLs are used in conjunction with other parameters they help yield a complete picture of the status and possible evolution of a project, and thereby enable well-informed decisions.

Recommendations for Future Work

01 Maturity metric standardization: suitable for all domains with varying degrees of complexity

02 Evolve with the times: When society changes, so must the ways people work change in order to stay relevant

03 New platform structures: Rather than top down, people work in flat organizations

04 Human aspects: Ways that regional and organizational culture affect the application of the scale

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Thank you, Cecilia Haskins, cha@usn.no