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Technical Paper

Case studies in estimating subsea systems' readiness level

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Abstract

Systems readiness level (SRL) is a metric defined for assessing progress in the development of systems. The methodologies to estimate SRLs are built on the technology readiness level (TRL), originally developed by NASA to assess the readiness of new technologies for insertion into a system. TRL was later adopted by governmental institutions and many industries, including the American Petroleum Institute (API). The TRL of each component is mathematically combined with another metric, integration readiness level (IRL), to estimate the overall level of readiness of a system. An averaging procedure is then used to estimate the composite level of systems readiness. The present paper builds on the previous paper by Yasseri (2013) and presents case examples to demonstrate the estimation of SRL using two approaches. The objective of the present paper is to show how the TRL, IRL, and SRL are combined mathematically.

The performance of the methodology is also demonstrated in a parametric study by pushing the states of readiness to their extremes, namely very low and very high readiness. The present paper compares and contrasts the two major system readiness levels estimation methods: one proposed by Sauser et al. (2006) for defence acquisition based on NASA's TRL scale, and another based on API's TRL scale. The differences and similarities are demonstrated using a case study.

Keywords: subsea production systems; technology readiness level; integration readiness level; system readiness level; system maturity

1. Introduction

An understanding of technology readiness is critical in making decisions about the use of new and/or existing components in a new system (Olechwski et al., 2015). The most widely used tool for readiness assessment is NASA's technology readiness level (TRL) scale. NASA introduced TRLs (Mankins 1995; 2009) in the 1970s, and in 1995 published a refined 9-level scale, along with with with the first detailed descriptions of each level (Azizian et al., 2009). Presently, the TRL approach is used in multiple industries and serves a similar purpose. Commercial implementations of TRLs are similar to NASA's nine-level scale. Fig 1 shows a generic nine-level TRL definition. Similar to the NASA scale, this generic scale begins with a technology in its very basic scientific form, and progresses to a proven technology in its actual operating environment.

TRL is a measure of an individual technology at a point in its development cycle, and not of a system's readiness. TRL on its own cannot indicate a system's readiness. TRL 1 through to TRL 8 on NASA's scale focus on the design, development and testing aspects of a system. TRL 4 and TRL 5 concern verification (not the validation of components). TRL 9 focuses on the 'operational' aspects of the components, as it is integrated with the system. Thus, the qualification of a component for TRL 8 and TRL 9 must be performed within the context of the system that uses it.

TRLs were not intended to address systems integration, i.e. assuring various components to work together perfectly in a system, nor to indicate that the technology will result in the successful development of a system (Gove, 2007). The wrong technology, or even the right technology which is improperly implemented, can be ineffective. The TRL scale is also used as an evaluation and planning tool to assess the readiness for the insertion of individual components into a system and to simplify the communications on the status of all components.

A system comprises core technology components and their linkages in accordance with the system architecture. According to Henderson and Clark (1990), two types of knowledge are needed: component and architectural (i.e. knowledge of how the

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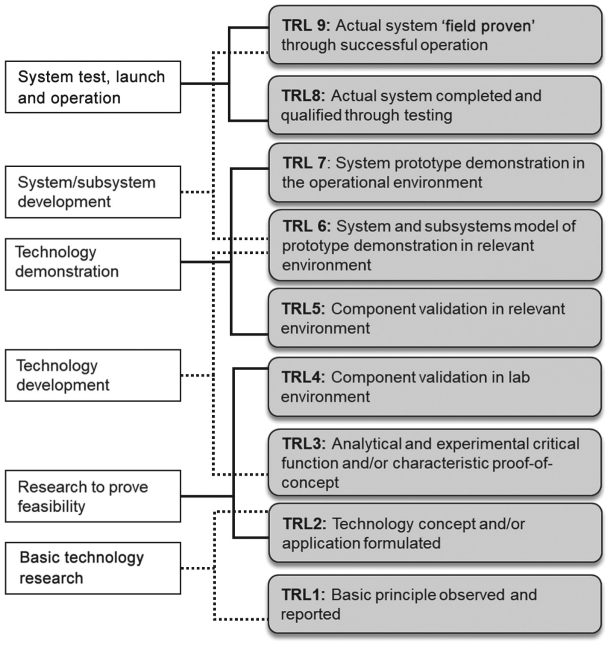

Fig 1: A generic NASA-type TRL scale (Nolte et al., 2004)

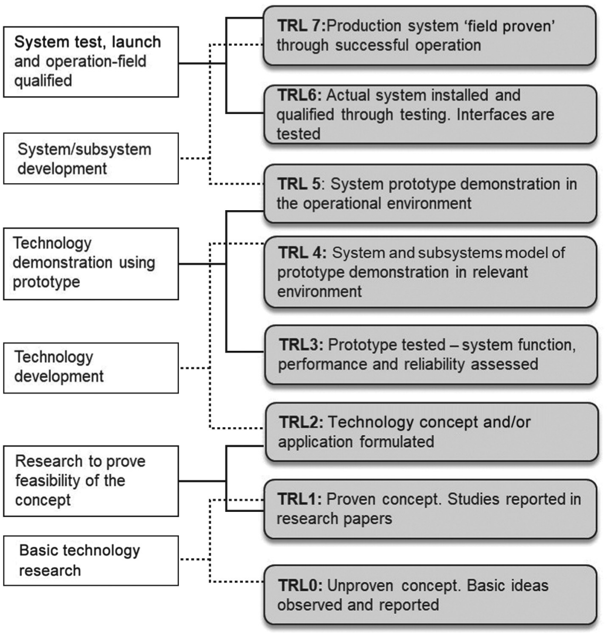

Fig 2: API (2009) TRL scale

components are linked together). Henderson and Clark (1990) emphasise that systems often fail because attention is given to the technology, while knowledge of the linkages and integrations is not fully addressed. They conclude that while the TRL provides the metric for describing component knowledge, it is important to find a metric that provides a description of architectural knowledge and integration.

Once the technology is sufficiently proven, it can be incorporated into a system and subsystem. Smith (2005) makes a distinction between readiness and maturity by noting that a system considered mature in one context, may not possess sufficient readiness for operation in a different environment. Bilbro (2007) used 'maturity' as part of the definition of 'readiness' and thereby implies a relationship between the two terms. However, some authors use these terms interchangeably (e.g. Azizian et al., 2009). Any ready technology is mature, but not all mature technology (in some systems) is ready for a different use. The present paper uses the term 'readiness' to include maturity and suitability for deployment; the terms system 'readiness' and system 'maturity' are used in the present paper to signify different things.

The two metrics of integration readiness level (IRL) and system readiness level (SRL) are architecture-based extensions to the TRL introduced by Sauser et al. (2007; 2008). Yasseri (2013) extended the American Petroleum Institute's (API; 2009) TRL definitions by defining IRL and SRL metrics suitable for use in subsea system developments with API's TRL. API (2009) adapted NASA's scale into a seven-stage scale (Fig 2; see Yasseri, 2013). API (2009) distinguishes three development levels: concept validation (TRL 0 to 2), technology validation (TRL 3 to 5), and system validation (TRL 6 to 7). Similar to NASA's TRL, API's TRL concentrates on individual technology being developed to be integrated with other components/sub-systems in a broader subsea system. Fig 3 compares the API TRL definition with a NASA-type scale. This adaptation fulfills the needs of the sanctioning authority for a harmonised scale to monitor the state of progress in a major investment project. Acceptable technology maturity has often been the principal driver, particularly in subsea systems, where availability is fundamental to customer requirements.

Generally, technology and system development should follow the same timeline (evolution), or maturation paths. A technology is inserted into a system based on its readiness, functionality and environmental readiness, and its ability to successfully interact with other components in the system. Many factors governing the development of a successful system are not always effectively implemented, but by considering IRL such oversights can be substantially reduced.

API's TRL levels 0 to 6 follow NASA's TRL levels 1 to 7, and API's level 7 combines NASA's levels 8 and 9. The dependencies between modules/components and the dependency of the subsystem/system to its environment are not explicitly addressed by API's TRL.

2. Domain mapping

A system is an aggregation of pieces of equipment and enabling products (including software)

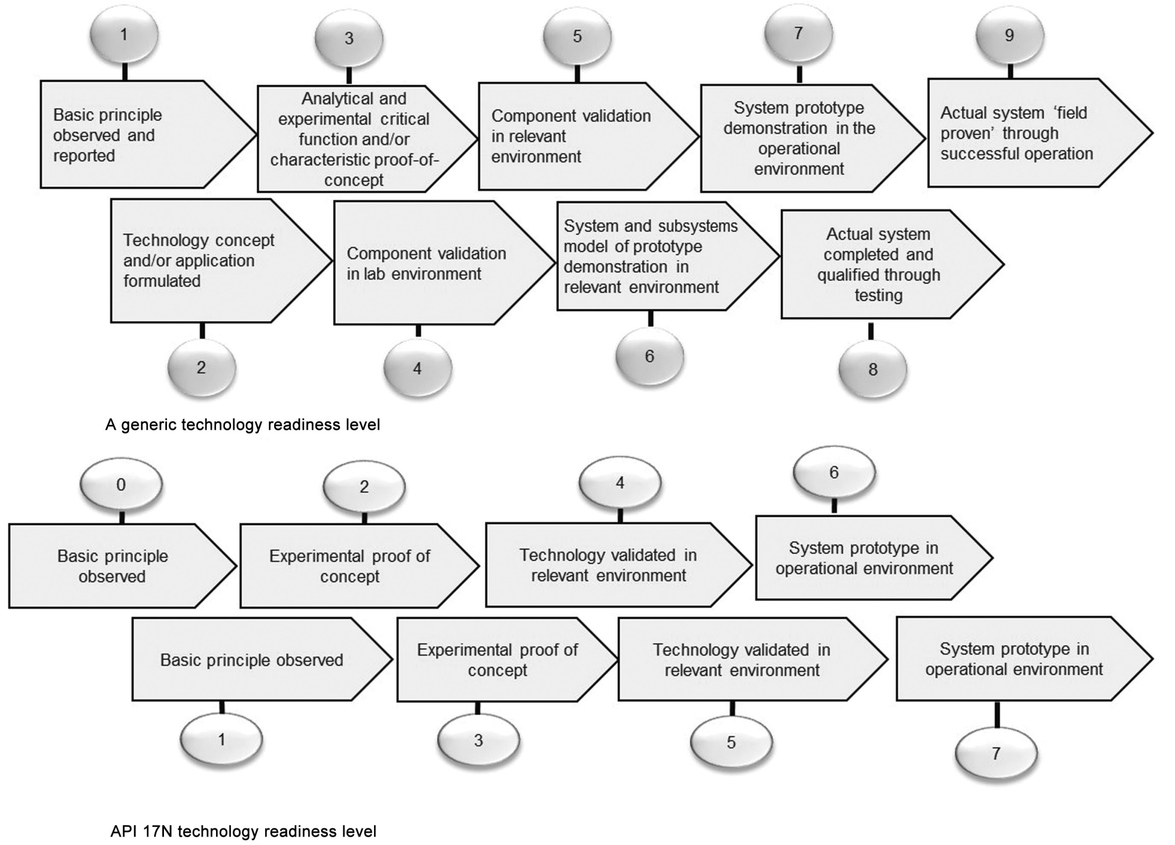

Fig 3: Comparison of NASA-type TRL scale with API (2009) TRL scale

to perform a mission. This arrangement of components and equipment (or subsystems) is the system's architecture. In the context of an oil and gas production system, system components include flowlines, Christmas trees, blowout preventers, actuated valves and pumps, that together enable a subsea production system to achieve its purpose. A system diagram or map shows the basic logical architecture, or abstraction, of a system and enables its visualisation. A system map shows every piece of functional equipment that is required to perform a function and how they are linked together.

There are several ways to map a system. For example, a schematic diagram of a chemical process uses symbols to represent the vessels, piping, valves, pumps, and other system equipment, indicating their interconnecting paths while omitting physical details. The schematic shows the intent and how the parts are supposed to interact with each other, i.e. the flow of fluid along its path. A schematic usually omits all details that are not relevant to understand interdependencies. In contrast, a construction drawing shows equipment as they are actually laid out and to scale, and can be used to build the system.

Two popular methods of representation of a system functional architecture (or alternatively, its structural elements) are the block diagram and the design structure matrix (DSM).

2.1. Block diagram

A block diagram is a representation of a system in which the principal, functions, parts, and equipment are represented by blocks connected by lines that show the relationships between the blocks. The block diagram is especially focused on the input and output of a system and does not consider the internal workings of the equipment. This principle is referred to as the black box in engineering, whereby the paths that get from input to output are unknown or left to be defined at a later stage.

Fig 4 shows the block diagram of a simple system comprising nine components, grouped into three modules at an advanced stage of the functional architecting. There are interfaces between the components within each module and the different modules. Interfaces between the two components are shown by double-headed arrows, implying that the readiness of two components to be integrated is interdependent. Single-headed arrows are used to show the direction of flow, not interdependencies.

2.2. Design structure matrix (DSM)

A DSM is a square matrix used to represent the relationships and dependencies between individual components of a system (Browning, 2016; Eppinger and Browning, 2012). The block diagram in Fig 4 is shown in Table 1 as a DSM. The network shown in

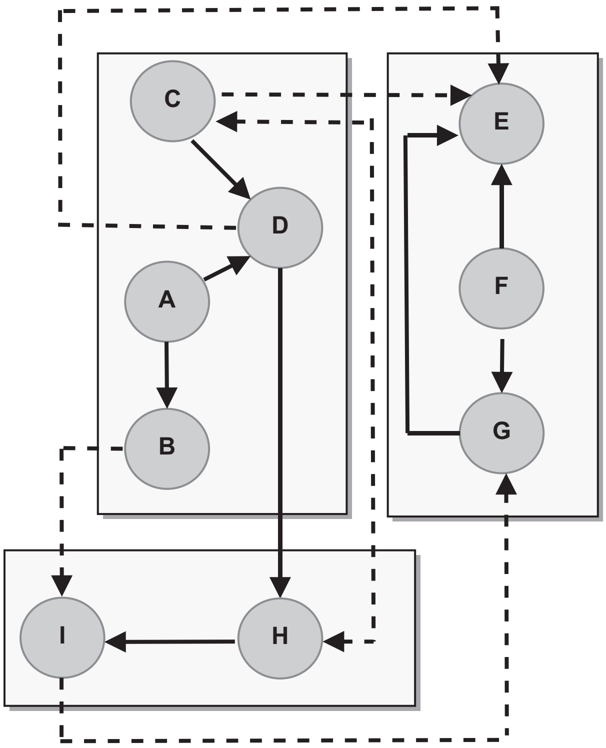

Fig 4: A directed graph network showing components of a system and their connectivity

Table 1 gives a view of the system's functional components, and how they must interface to achieve the required mission. The components are shown as rows and columns in the matrix, and the components are listed in the same order along both axes. Component interactions are represented by an 'x'; components A and F do not require input from the other components, whereas B, C, D, E, G, H and I receive input. By reading down a column, it is possible to see that a component provides input to others in its associated row. When reading across a row in the matrix, it is possible to see that a component in the row receives input from the component in the corresponding column.

A subsea system can be organised into a hierarchical structure, e.g. subsystem, sub-sub systems, and assemblies or components (Yasseri, 2015a). This hierarchical representation avoids problems related to presenting extremely large matrices by shifting the focus to various levels in the hierarchy, enabling the analysis of a system at different levels and details. In general, the DSM analysis only considers relationships across components (at the same level), and not within components (done at the next level of the hierarchy).

Table 1: DSM of the functional block diagram shown in Fig 4

	A	B	C	D	E	F	G	H	I
A									
B	X								
C								X	
D	X		X				X		
E			X	X		X	X		
F									
G									X
H			X	X					
I		X						X	

3. Sauser et al.'s method for system readiness level estimation

TRL provides an indication of the components' readiness status. However, it is useful to have a metric that provides a description of the components integrated into the system, i.e. how components relate to each other and work together. It is important that all stakeholders have the same understanding when evaluating the integration readiness, or system readiness, and how TRL relates to IRL and SRL. SRL based on the component integration and interoperability is more relevant for identifying lagging or critical technology, especially if a substitute must be sought.

The present section describes a concept originally proposed by Sauser et al. (2006) for the development of an SRL scale that incorporates the readiness level of all components of the entire system without exception. The original Sauser et al.'s (2006) definition of SRL is based on the NASA-type TRL scale. They introduced a new metric for integration, namely the integration readiness level (IRL), and proposed a mathematical method for combing TRL and IRL for estimating SRL. The resultant SRL scale can provide an assessment of the progress of overall system development and identify potential areas that require further work.

Gove (2007) and Sauser et al. (2010) identified the requirements for IRL as:

1) Provide an integration-specific metric to determine the integration maturity between two or more configuration items, components and/or subsystems.
2) Provide a means to reduce the uncertainty involved in maturing and integrating new technology into a system.
3) Provide the ability to meet system requirements during the integration assessment, so as to reduce the integration of obsolete technology over less mature technology.
4) Provide a common platform for the maturity assessment of new system developments and new technology insertion. Based on these requirements, Sauser et al. (2010) proposed a 9-level IRL as described in Table 2.

Table 2: Definitions of TRL and IRL for the US Department of Defense (Sauser et al., 2010)

	Technology (components)				Interrogation (interfaces)
TRL	**Description**			**IRL**	**Description**
9	Integration is mission proven through successful mission operations	Demonstration	Demonstration	9	Execute a support program that meets operational support performance requirements and sustains the system in the most cost-effective manner over its total life cycle
8	Actual system completed and qualified through test and demonstration			8	Actual integration completed and mission qualified through test and demonstration in the system environment
7	System prototype demonstration in relevant environment			7	The integration of technologies has been verified and validated with sufficient detail to be actionable
6	System/subsystem model demonstration in relevant environment	Construct	Integrate	6	The integrating technologies can accept, translate and structure information for its intended application
5	Component and/or breadboard validation in relevant environment			5	There is sufficient control between the technologies necessary to establish, manage and terminate the integration
4	Component and/or breadboard validation in laboratory environment			4	There is sufficient detail in the quality and assurance of the integration between technologies
3	Analytical and experimental critical function and/or characteristic proof of concept	Research	Combine	3	There is compatibility between technologies to orderly and efficiently integrate and interact
2	Technology concept and/or application formulated			2	There is some level of specificity to characterise the interaction between technologies through their interface
1	Basic principles observed and reported			1	An interface between technologies has been identified with sufficient detail to allow the characterisation of the relationship

The introduction of an IRL to the assessment process provides a means of checking the technology's position on an integration readiness scale. Since both the technologies and integration elements are assessed using a numerical scale, it is possible to combine the IRL and TRL of all components (Yasseri 2016) and generate a composite metric for the overall system readiness (Sauser et al., 2008). The SRL matrix comprises one element for each of the constituent technologies and quantifies the readiness level of a specific technology with respect to each technology in the system. TRL and IRL values were normalised from the original 1 to 9 levels by dividing each element by 9. When no integration is present between two technologies, an IRL value of 0 is entered. For integrations to itself, a non-normalised IRL value of 9 or normalised value of 1 is used. The integration with itself was introduced (the diagonal line in the DSM matrix) to perform the matrix multiplication.

TRL is defined as a vector with n entries, as shown in equation 1, where TRL_i is the TRL of technology i:

$$[TRL]_{n,1} = \begin{bmatrix} TRL_1 \\ TRL_2 \\ \dots \\ TRL_n \end{bmatrix} \tag{1}$$

Matrix IRL illustrates how the technologies are integrated with each other from a system perspective. For a system with n technologies, IRL is defined in equation 2, where IRLij is the IRL between technologies i and j. The hypothetical integration of a technology i to itself is denoted by $[TRL]_{ii}$:

$$[TRL]_{n\times n} = \begin{bmatrix} TRL_{11} & TRL_{12} & \cdots & TRL_{1n} \\ TRL_{21} & TRL_{22} & \cdots & TRL_{2n} \\ \dots & \dots & \dots & \dots \\ TRL_{n1} & TRL_{n2} & \cdots & TRL_{nn} \end{bmatrix} \tag{2}$$

In these matrices, the standard TRLs and IRLs corresponding to values 1 to 9 should be normalised.

In any system, each of the constituent technologies is connected to a minimum of one other technology through a bi-directional integration. The manner in which each technology is integrated with other technologies is used to formulate an equation for calculating SRL. This SRL equation comprises the TRL and IRL values of the technologies and the interactions that form the system. In order to calculate a value of the SRL from the TRL and IRL values, TRL and IRL matrices are normalised. An SRL matrix is obtained from the product of the TRL and IRL matrices, as shown in equation 3:

$$[SRL]_{n \times 1} = [IRL]_{n \times n} \times [TRL]_{n \times 1} \tag{3}$$

The SRL matrix comprises one element for each of the constituent technologies and quantifies the readiness level of a specific technology with respect to each technology in the system; it also accounts for the development state of each technology through the TRL. For a system with n technologies, SRL is as shown in equation 4:

$$[SRL] = \begin{bmatrix} SRL_1 \\ SRL_2 \\ \dots \\ SRL_n \end{bmatrix} = \begin{bmatrix} IRL_{11}TRL_1 + & IRL_{12}TRL_2 + & \cdots & +IRL_{1n}TRL_n \\ IRL_{21}TRL_1 + & IRL_{22}TRL_2 + & \cdots & +IRL_{2n}TRL_n \\ \dots & \dots & \dots & \dots \\ IRL_{n1}TRL_1 + & IRL_{n2}TRL_2 + & \cdots & +IRL_{nn}TRL_n \end{bmatrix}, \tag{4}$$

where $IRL_{ij} = IRL_{ji}$.

These values will be within the interval (0 and n); hence, for each technology, i, its corresponding SRL_i is divided by n_i (n_i is the number of integrations of technology I; each technology is dictated by the system architecture, including its integration to itself, to obtain its normalised value between 0 and 1. The SRL for the complete system is the average of all normalised SRL values, as shown in equation 5:

$$SRL_{estimate} = \frac{\dfrac{SRL_1}{n_1} + \dfrac{SRL_2}{n_2} + \cdots + \dfrac{SRL_n}{n_n}}{n} \tag{5}$$

Equation 5 gives an SRL assuming there is no modularisation. If a system consists of m modules, then:

$$SRL_{estimated} = \frac{SRL_{M1} + SRL_{M2} + \ldots + SRL_{Mn}}{m}, \tag{6}$$

where $SRL_{M1} = \dfrac{SRL_{Comp1} + SRL_{Cop2} + \ldots + SRL_{Comp\,k}}{k}$,

and k is the number of components in module 1. SRL estimations for the remaining modules are similar.

The SRL metric can be used to determine the readiness of a system and its status within a developmental lifecycle. Table 3 presents an example of how the various levels of the SRL scale can correlate to an acquisition life cycle. Table 4 presents an SRL scale

Table 3: Banding of $SRL_{estimated}$ according to Sauser et al. (2010)

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

Table 4: SRL scale according to the US Department of Defense (2011) integrated defense acquisition, technology, and logistics life cycle

SRL	Definition
9	The system has achieved initial operational capability and can satisfy mission objectives
8	System interoperability should have been demonstrated in an operational environment
7	System threshold capability should have been demonstrated at operational performance level
6	Whether the system component can be integrated and should have been validated
5	System high-risk component technology development should have been complete; low-risk system components
4	System performance specifications and constraints should have been defined and the baseline allocated
3	System high-risk immature technologies should have been identified and prototyped
2	System materiel solution should have been identified
1	System alternative material solutions should have been considered

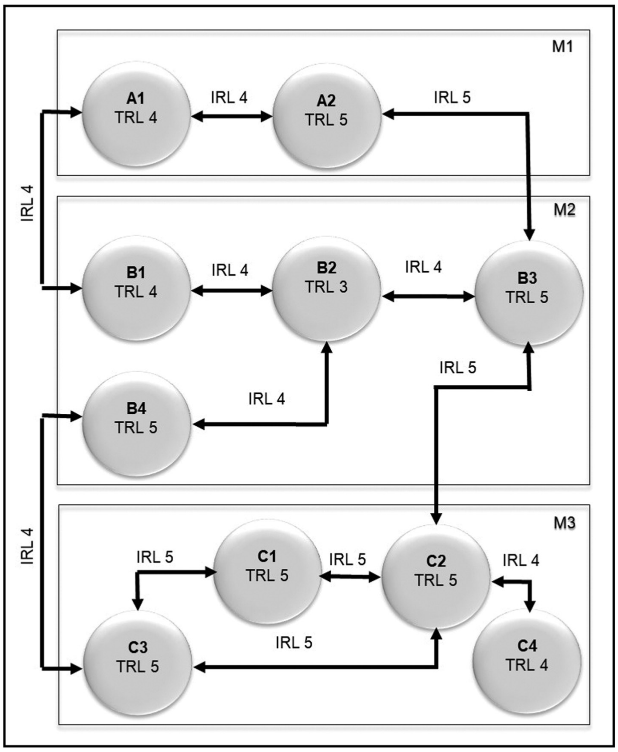

Fig 5: A simple system comprising ten components arranged into three modules. No integration with the environment is required

according to the US Department of Defense (2011). The results of equation 5 can be multiplied by 9 to de-normalise it, and the resulting figure can be used in conjunction with entries from Table 4. It is important to note that many military and space systems cannot be verified (levels 8 and 9) in their operational environment until deployed. Likewise, many systems are part of an evolutionary life cycle in which the final maturity will be verified once deployed or in the next generation.

4. Example case 1: SRL calculation according to the approach by Sauser et al.

Fig 5 shows a simple system comprising ten technologies (components): A1 to A10. It is not necessary for this system to be integrated into its operational environment, but it should be able to operate within its operational environment. Demonstration of TRL 8 and 9 is not possible until the system is deployed; therefore, proof that the system operates may be done in a simulated environment (e.g. weapon systems) or not at all (e.g. aerospace vehicles). This system can be considered as a single ten-component system or a system which comprises ten modules. Alternatively, some technologies may be bundled together to create subsystems so that more vendors can be involved, or for the purpose of parallel manufacturing.

Table 5 shows a DSM for this ten-component system as shown in Fig 5. The diagonal terms are the maximum TRL in the scale (9 in NASA scale). The off-diagonal terms are the IRL of two interfacing components. Columns 1 to 14 of Table 5 are part of a larger table employed for all calculations. Columns 15 to 29 of the larger table are shown in Table 6. The TRL levels are values 1 to 9; the IRL values also range from 1 to 9. Before the matrix calculation is performed, these values are normalised by being divided by 9. For example, an IRL of 9 has a normalised value of $9/9 = 1$, and an IRL of 5 has a normalised value of 5/9 or 0.556.

The values of the IRLs are specified in Fig 5 and have been inserted in the matrix (Table 5, columns 5 to 14). Each of the components of a system is connected to at least one other component. The TRL of each component is entered in the third column of Table 5. It is assumed that the integration is bi-directional, namely, that the IRL is the same in each direction, and thus that the DSM is symmetric.

Maturity is differentiated from readiness. For example, component 7 in Fig 5 has been in an operational system for some years, but when it is used for a new system, it is not considered ready for the new situation and enters into the new system at level 6, or level 7 on NASA scale. Attainment of levels 8 and 9 must be proven within the environment of the new system. With the exception of mature technologies, all new technologies in the new system mature along the same timeline, though some may be ahead of others. However, the interface between two components may drag down the technology's readiness, which otherwise matures faster in other aspects. Thus, it is not possible for a technology to be at level 7, and its linkage to other components in the system at level 2 or 3. The large difference is an indication that the mature technology must enter at a lower TRL, commensurate with the readiness of its linkage. In conclusion, if the IRL is low, then the TRL must be revised downward.

The product $[\mathrm{IRL}]_{10\text{-by-}10} \times [\mathrm{TRL}]_{10\text{-by-}1}$ yields a resultant 10×1 column matrix (column 26) using equation 4. In order to calculate a composite SRL from the component TRL and IRL values, an SRL matrix is generated from the product of the IRL and TRL matrices, as per equation 4. For example, for row 4 of column 26, $1 \times 0.444 + 0.56 \times 0.566 + 0.44 \times 0.444 + \ldots = 0.951$. The rest of column 26 is populated similarly.

Each component's SRL is calculated by dividing the value in column 26 by the total number of integrating components (including integration with itself, column 27). Results are then entered in

Table 5: DSM for the system shown in Figure 5

1	2	3	4	5	6	7	8	9	10	11	12	13	14
2			Components	Components									
3		TRL		A1	A2	B1	B2	B3	B4	C1	C2	C3	C4
4	M1	4	A1	9	5	4							
5		5	A2	5	9			4					
6	M2	4	B1	4		9	4						
7		5	B2			5	9	4	4				
8		5	B3		4		4	9			4		
9		5	B4				4		9			4	
10	M3	4	C1							9	5	5	
11		5	C2					4		5	9	5	4
12		5	C3						4	5	5	9	
13		4	C4								4		9

Table 6: Columns 15 to 29 of calculations for example case 1 (continuation of Table 5; refer also to figure 5)

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Normalised IRL										Normalised TRL	Sum of TRLc times IRLc	Number of interfacing components	Component SRL	Module SRL
1	2	3	4	5	6	7	8	9	10					
1.00	0.56	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.444	0.951	3	0.317	0.333
0.56	1.00	0.00	0.00	0.44	0.00	0.00	0.00	0.00	0.00	0.556	1.049	3	0.350	
0.44	0.00	1.00	0.44	0.00	0.00	0.00	0.00	0.00	0.00	0.444	0.889	3	0.296	0.324
0.00	0.00	0.56	1.00	0.44	0.44	0.00	0.00	0.00	0.00	0.556	1.296	4	0.324	
0.00	0.44	0.00	0.44	1.00	0.00	0.00	0.44	0.00	0.00	0.556	1.296	4	0.324	
0.00	0.00	0.00	0.44	0.00	1.00	0.00	0.00	0.44	0.00	0.556	1.049	3	0.350	
0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.56	0.56	0.00	0.444	1.062	3	0.354	0.338
0.00	0.00	0.00	0.00	0.44	0.00	0.56	1.00	0.56	0.44	0.556	1.556	5	0.311	
0.00	0.00	0.00	0.00	0.00	0.44	0.56	0.56	1.00	0.00	0.556	1.358	4	0.340	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.44	0.00	1.00	0.444	0.691	2	0.346	
										Composite SRL based on individual components			0.3311	
										Composite SRL based on modules				0.3315
										Multiply by 9 to reserve normalisation			2.980	2.983

column 28. For example, component C2 requires five total integrations: components B3, C1, C3 and C4 and integration with itself. Thus, the component SRL for C2 is 1.556/5 = 0.311. Table 7 shows SRL for all components.

The composite SRL is the average of the component SRLs (equation 8). As with any calculation involving an average, the analyst needs to be aware of the potential to mask an SRL that is significantly lagging or leading the average, reiterating the importance of assessing and monitoring the individual component SRLs.

Some modules have reached level 5 status on the TRL scale, but a few do not. The intention is to achieve the requirements of TRL 5 and assemble the system for integration testing. The SRL index according to Sauser et al. (2006; 2010) is 0.3311 (based on components), which is used in conjunction with Table 3. Multiplying this number by 9 gives a de-normalised value of 2.980, which can be used with Table 4. Column 28 shows the same type of calculation based on modules. The SRL using modules' SRL is 0.3315, which is slightly higher. This difference is a result of the two-tier averaging of the module-based SRL.

The component SRLs provide an indication of the readiness of the individual component and its associated integrations. Examination of the individual component SRL values relative to each other identifies those components that are lagging. Composite SRL values are translated to whole numbers consistent with TRL and IRL scaling for ease of interpretation.

The SRL shown in this section resulted in a composite SRL of 0.3315. Using the SRL translation model of Table 3, this system is at the technology development stage. Alternatively, multiplying 0.3315 by 9 gives 2.98, which translates to an SRL of 3 in conjunction with Table 4. The SRL calculated in this example is a snapshot in time, thus it is critical to measure the system readiness at multiple points along the life cycle.

4.1. System readiness definition based on API TRL scale

Subsea production systems (SPS) are becoming more complex owing to the requirements of high availability and minimal intervention for repair. Many new technologies are inserted to achieve these goals. The software is also increasingly used to control SPS, thus adding to the level of complexity. It is not surprising that many designers are continually searching for the cause of unexpected failures and unacceptable behaviour in systems meant to be 'ready' for operation. There is a need to assess and measure, with high confidence, a system readiness level during the development life cycle. The readiness of equipment for use is assessed on its own merit. The aim of this and the next section is to demonstrate the notions of readiness proposed by Yasseri (2013; 2016) and Yasseri et al. (2018a; 2018b) through case studies.

Achievement of API's TRL 4 is one of several pieces of evidence that is used in the decision-making process for committing to major capital

Table 7: IRL and SRL definition compatible with API's TRL (Yasseri, 2013)

Phase	TRL	Development stage	IRL	Development stage	SRL	Development stage
System validation	7	Field-proven production system	7	Integration is field-proven through successful operations	7	Field proven operational system
	6	System installed. Production system installed and tested	6	Integration is completed and qualified through sufficient and rigorous testing in the marine environment	6	The system is installed and tested. Commissioning in progress
Technology validation	5	System tested. Production system interface tested	5	The integration has been verified and validated with sufficient detail for the system to be deployable	5	Manufacturing and installation in progress
	4	Environment tested. Pre-production system environment tested	4	There are sufficient details to assure interoperability between technologies necessary to establish, manage and assure the integration	4	Detail design and final procurement
	3	Prototype tested. System function, performance and reliability tested	3	There is sufficient detail in the control and assurance of the integration between technologies to deliver the required functionality	3	Front-end engineering. Sourcing of long lead items
Concept validation	2	Validated concept. Experimental proof of concept using physical model tests	2	There is sufficient evidence of compatibility between technologies within the system. Namely, they will work together and can be integrated with ease	2	Concept selection. An optimal concept has emerged
	1	Demonstrated concept. Proof of concept as desk study or research and development experimentation	1	There is some level of specificity to the system functionality to allow identification of linkage between technologies	1	Concept refinement. Two or more competing concepts are being considered
	0	Unproven concept. Basic research and development in progress	0	The interface, i.e. the linkage, between technologies can be identified and characterised with sufficient clarity	0	Concept definition. Various ideas are being considered or discounted

Table 8: Definitions of the environmental readiness scales compatible with API's TRL scale

Environmental readiness level achieved	Activity	Description	Focus
7	Proving technology over time	Technology is field proven	Operation
6	Qualification of the installed system	The system is installed, tested and commissioned	Assuring the integration of the system and the environment
5	System qualification testing	System test is complete	Integration of the system
4	Environmental qualification testing	Environmental testing is complete	Enhancing reliability by reducing uncertainties
3	Prototype qualification testing	The prototype is tested. Technology is robust and usable	Real size testing
2	Concept validation	Technology is validated	Scale testing
1	Conception	Technology is demonstrated	Experimenting

investment (Yasseri, 2014). Thus, TRL 4 is critical for making the decision on whether to go forward with the investment. TRL 5 is the most important technical stage during the subsea development process. At API's TRL 5 stage readiness of all necessary components must be demonstrated; it also involves a demonstration that the components work together as a system. Thus, achieving a TRL of 5 is a prerequisite for the integration and installation of assemblies. Validation at this level must go beyond discrete components and must consider testing the assembled components (or subsystems), testing at the quayside, and possibly in shallow water (i.e. a relevant environment) and/or the operational environment (Table 7).

Whereas an aerospace vehicle should be operated in its environment, a subsea system must be integrated with its environment and operate within it. Thus, the environment readiness must be included in the SRL assessment. All equipment must be supported and secured on the seabed using one of several means, e.g. gravity base, suction piles or ordinary piles, and preparing the seabed for the reception. While the technology readiness of the seabed is not meaningful, the integration of equipment with the seabed requires attention. The present paper uses a seven-level scale to assess the environmental readiness level (see Table 8).

5. Example case 2: SRL calculations for SPS

Fig 6 shows a system that is similar to that shown in Fig 5 but is arranged into three modules, each of which must be integrated with the environment. The numerical values of TRL and IRL are kept the same; Example 2 refers to the API scale, while the NASA scale was used in example 1. The three modules in Fig 6 require integration with the operational environment.

Table 9 details SRL calculations. Columns 4 to 15 in Table 9 show an asymmetric DSM matrix resulting

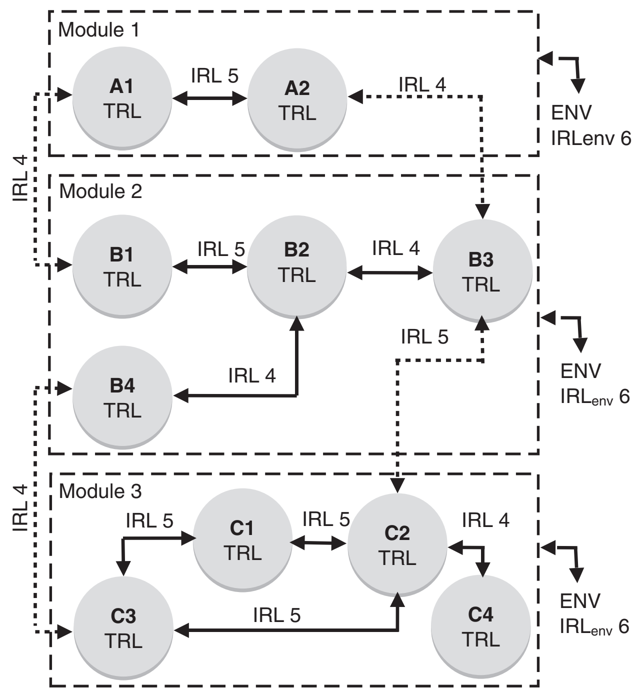

Fig 6: A simple system of a subsea system that must be integrated with the seabed

from the assumption that two interfacing components could have different TRLs, but their integration readiness levels are the same and equal to the least ready component owing to mutual dependency. In general, the matrix does not need to be symmetric, as the symmetry assumption is not necessary for the application of the method. Column 15 is the environment readiness index (Table 9).

Entries in column 16 in Table 9 with the heading 'Average IRL' is the arithmetic average of all IRLs in that row, determined by summing up the IRLs of all interfacing components across the row and dividing it by the number of interfaces. For example, for the first row $(4 + 5)/2 = 4.5$, 2 is the number of components to be integrated, not integration with itself. Column 17 (with the heading 'TRL*Average IRL') gives the results of multiplication of the component's TRL and the average of its

Table 9: Calculation of SRL for the system of Fig 6 according to the method of Yasseri (2013; 2016)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
2	**Modules**	**Components**		**Components**											Average IRL	TRL*Average IRL	SQRT	Module SRL
3				**A1**	**A2**	**B1**	**B2**	**B3**	**B4**	**C1**	**C2**	**C3**	**C4**	**ENV**				
4			TRL	IRL matrix														
5	**M1**	**A1**	4		**5**	**4**								**5**	4.50	18.00	4.24	4.41
6		**A2**	5	**5**				**4**							4.50	22.50	4.74	
7	**M2**	**B1**	4	**4**			**5**								4.50	18.00	4.24	
8		**B2**	5			**5**		**4**	**4**					**5**	4.33	21.67	4.65	4.38
9		**B3**	5		**4**		**4**				**4**				4.00	20.00	4.47	
10		**B4**	4				**4**					**4**			4.00	16.00	4.00	
11	**M3**	**C1**	4								**5**	**5**		**5**	5.00	20.00	4.47	4.51
12		**C2**	5					**4**		**5**		**5**	**4**		4.50	22.50	4.74	
13		**C3**	5						**4**	**5**	**5**				4.67	23.33	4.83	
14		**C4**	4								**4**				4.00	16.00	4.00	
15																	SRL =	3.75

IRLs; for example, in row 1 4 × 4.5 = 18. Column 18 gives the root of the mean of squares (RMS) for each component. For example, the square root of column 17 is 4.24 (noted in column 18), giving a composite component readiness index.

The root of the mean of the sum of squares for the first module is:

$$M_{1-R} = \sqrt{\frac{18.0 + 22.5 + 18.0}{3}} = 4.41 \qquad (7)$$

The number 3 in the denominator is the number of components of the module M1. Alternatively:

$$\mathrm{M}_{1-\mathrm{R}} = \sqrt{\frac{(4.24)^2 + (4.74)^2 + (4.24)^2}{3}} = 4.41 \qquad (8)$$

An estimate of the system readiness level is given in Yasseri (2013):

$$\mathrm{SRL}_{\mathrm{estimate}} = \sqrt{\frac{(5/7)\times(4.41)^2 + (5/7)\times(4.38)^2 + (5/7)\times(3.39)^2}{3}} = 3.45, \qquad (9)$$

where 7 is the highest score for the environmental readiness scale (Table 8) and is used for the normalisation purpose, and 3 is the number of modules. Using a value of 3.45 in Table 1, the system must be at the assembly and installation stage; if the project schedule dictates a different level then reasons must be given for this.

From a metrics point of view SRL_{est} and SRL should measure the same things on the same scale. However, SRL is defined (Table 7), while SRL_{est} is derived by aggregation of attributes of all components using calculations. The estimate of system readiness reaches its highest level from below, as it measures the system readiness as a whole, and not its elements. If all components mature simultaneously along the same path, then SRL_{est} approaches SRL. More inter-dependencies will increase the gap between SRL_{est} and SRL if the IRLs are not at the same level as the TRLs.

The component readiness level and system readiness level should be distinguished. For example, in the case of a component being investigated when it achieves TRL 6, although the investigation is in the context of the intended system in its environment, the focus is on the individual component, not the whole system.

This index informs management when and where to intervene if the system readiness is lagging behind schedule. The entries in each row identify which components require closer management attention. A tightly controlled project ensures that TRL, IRL, and SRL closely follow each other.

While there are differences between the present paper's methodology and that of Sauser et al. (2006, 2008 and 2010) method can be applied to this example. Columns 1 to 14 would be the same as shown in Table 9; Table 10 shows the rest of the larger table. Sauser et al. (2006, 2008 and 2010) include integration with itself (see column 29 in Table 10 for the count of interfaces), and do not consider that the module should be integrated with its environment.

Table 10: Calculation of SRL for the system shown in Fig 6 using the method of Sauser et al (2010). Columns 1 to 14 are the same as given in Table 9.

15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Components										Normalised TRL	Sum of TRLc × IRLc	Number of interfacing components	Component SRL	Module SRL
A1	A2	B1	B2	B3	B4	C1	C2	C3	C4					
Normalised IRL matrix														
1.00	0.71	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.571	1.408	3	0.469	0.490
0.71	1.00	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.00	0.714	1.531	3	0.510	
0.57	0.00	1.00	0.57	0.00	0.00	0.00	0.00	0.00	0.00	0.571	1.306	3	0.435	0.479
0.00	0.00	0.71	1.00	0.57	0.57	0.00	0.00	0.00	0.00	0.714	1.939	4	0.485	
0.00	0.57	0.00	0.57	1.00	0.00	0.00	0.57	0.00	0.00	0.714	1.939	4	0.485	
0.00	0.00	0.00	0.57	0.00	1.00	0.00	0.00	0.57	0.00	0.714	1.531	3	0.510	
0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.71	0.71	0.00	0.571	1.592	3	0.531	0.501
0.00	0.00	0.00	0.00	0.57	0.00	0.71	1.00	0.71	0.57	0.714	2.367	5	0.473	
0.00	0.00	0.00	0.00	0.00	0.57	0.71	0.71	1.00	0.00	0.714	2.041	4	0.510	
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.57	0.00	1.00	0.571	0.980	2	0.490	
										Composite SRL based on component			0.4899	
										Composite SRL based on component				0.4899
										Reverse normalisation			3.429	3.429

Table 11: DSM and SRL assessment of the system shown in Fig 7

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
2	Modules	Components	TRL	Components											
3				A	B	C	D	E	F	G	ENV		TRL* Average IRL		
4				IRL matrix								Average IRL		SQRT	Module IRL
5	M1	A	4	**A**	**4**	**4**				**4**		4.00	16.00	4.00	
6		B	5	**4**	**B**		**4**			**5**		4.33	21.67	4.65	
7		C	4	**4**		**C**	**5**	**4**				4.33	17.33	4.16	
8		D	5		**4**	**5**	**D**		**4**		6	4.33	21.67	4.65	4.37
9	M2	E	5			**4**		**E**	**4**	**5**		4.33	21.67	4.65	
10		F	4				**4**	**4**	**F**	**4**		4.00	16.00	4.00	
11		G	5	**4**	**5**			**5**	**4**	**G**	6	4.50	22.50	4.74	4.47
12														SRL=	4.09

Table 10 gives an SRL index of 0.4899, and when multiplied by 7 this yields 3.429, which may be rounded up to 4. These results are not substantially different from the earlier values. This is not the case, however, when the environmental readiness is very low.

There is a distinction between critical and necessary technology. In principle, every piece of equipment in a system is necessary, since if it is not needed it can be eliminated. However, only a few pieces of equipment may be critical, since there may be no substitutes for them, and without them, the intended system will not perform. In subsea practice, no subsystem, assemblies (or large components) are excluded from the assessment; all are considered necessary. The level of detail is decided by the assessor(s), drawing on help from the subject expert. This suggests that the purpose of TRL in the subsea industry is to ensure the readiness of the components for insertion into the system.

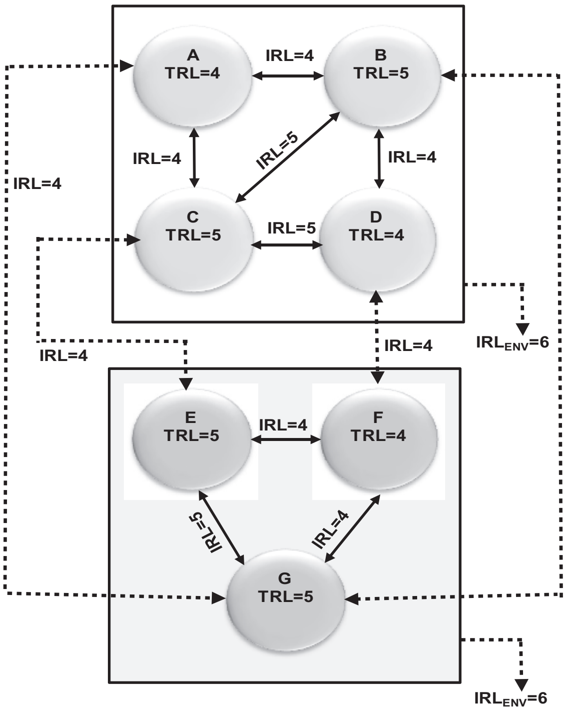

Fig 7: A system comprising two modules

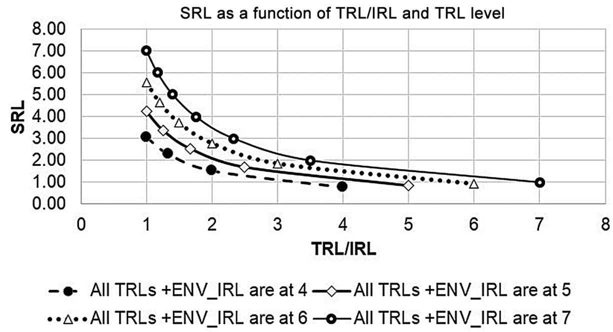

Fig 8: SRL as a function of TRL and TRL/IRL

6. Discussion

In designating interfaces between two components, the definition of the interactions between these interfaces is important (Yasseri, 2015b). In addition to the transmission of forces, moments and displacements between modules, there is also the transmission of fluid and energy, and data exchange. There are three possible forms of information exchange:

- **Internal interaction:** Referring to information exchanged within a single module.
- **External interaction:** Comprising information exchanged between two or more modules.
- **Boundary interaction**: Occurring at the boundaries of the model, interacting with entities outside the project such as vendors, installation contractors, etc.

According to Pimmler and Eppinger (1994), there are four types of interactions when integrating two technologies: physical connection, material flow, information flow, and energy exchange. The interaction strengths are the level or degree of interaction between the components. The DSM used shows the absence or presence of interaction, and it is assumed the numerical value of IRL will also account for the importance and strength of the interaction; otherwise, another layer needs to be added to the calculation.

All major subsea equipment must be laid on the seabed and secured, e.g. by foundation slabs, suction piles or conventional piles. There may also be a need for seabed preparation. With the exception of the shore approach and shipping channels, pipelines are not buried; however, the seabed may require sweeping or trenching. The need for a subsea system to be integrated with its environment differentiates it from other systems, such as aerospace vehicles or weapons. The present paper differs from the method originally presented by Sauser et al. (2006) as it includes the integration with the environment in addition to the method of estimating the SRL.

Since the purpose, context and approach of the present study, and that of Sauser et al. (2006, 2008 and 2010) differ, a qualitative comparison of the two approaches provides limited insight. A limited parametric study of the current proposal may be useful. The simple system shown in Fig 7 is used to demonstrate the behaviour of the current method when the ratio of TRL: IRL changes. This system consists of two modules, both of which must be integrated with the environment.

SRL estimation of modules and the system shown in Fig 7 are shown in Table 11. These calculations show that the system has achieved SRL level 4, which is the minimum TRL defined for some component. The environmental readiness keeps back the SRL until it reaches $IRL_{env} = 7$.

Fig 8 shows when the TRL and IRL_{Env} are kept at the same level, but the TRL: IRL ratio is changed; it also shows when the IRL is lagging behind the TRL. For a well-managed project, the TRL: IRL ratio should be close to one since the readiness of a technology to be integrated with other technologies will affect its TRL.

7. Conclusions

TRLs provide a common understanding of the status of a technology during its development life cycle, which can also act as a means of assessing and managing risk, and making decisions concerning funding and implementation of technology. As with any management tool, there are certain limitations to its use. Assigning a TRL rank is not a quick task.

Two new metrics, namely IRL and SRL, introduced in previous papers by Yasseri (2013; 2016) for the subsea oil and gas production systems, were explored using example cases. Integration readiness level (IRL) indicates the readiness of two interfacing components to be brought together. The system readiness level (SRL) is a measure of the readiness of the entire system to be deployed, and combines TRL with IRL into a system readiness metric. Comparing the estimated SRL and values in the SRL table indicates the level of system readiness. These three indices provide part of the information required for project sanction to allow a project to move through the gate to the next phase of development in a stage-gate process.

Technology, integration and systems development follow similar evolution, or maturation, paths. The SRL methodology provides decision-makers with a snapshot of a system's state of readiness for deployment, and quantifies the level of component-to-component integration during system development, thus helping to improve system performance. Implementation of the SRL methodology aids decision-makers in identifying programmatic and technical risk areas.

The proposed subsea system assessment framework was then compared and contrasted with the SRL methodology originally proposed by Sauser et al. (2006) for defense acquisition.

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