

# System Readiness Level Estimation of Oil and Gas Production Systems

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## ABSTRACT

This paper explores further and describes the System Readiness Level estimation for means of production in the oil and gas industry, through a case study. The concept as Technology Readiness Level (TRL) originally promoted by NASA and was then adopted by government agencies and industries across the USA and Europe. TRL was adopted by API (API 17N) and tailored for the assessing the readiness of subsea components for inclusion in subsea production systems. The API's TRL has been recently extended by introducing two more metrics namely, the Integration Readiness Level (IRL) and the System Readiness Level (SRL). SRL is a mathematical combination TRL and IRL and is a metric for assessing progress in developing major subsea systems. Standard assessment metrics, such as Technology Readiness Levels (TRL), do not sufficiently evaluate the modern complex systems. Building on the previous publications [43] the SRL calculation method is expanded and expounded by adding a system engineering framework for the process of SRL estimation. Explained in some detail, in this paper, which produces more consistent results. Using an error averaging method, SRL is calculated by combining the TRL of each component with IRL, which expresses the readiness of each of these components to be integrated with other components of the system. To facilitate the calculation the Design Structure Matrix (DSM) is used both to visualise components and perform the necessary arithmetic.

## 1. Introduction

A better understanding of the technology readiness is critical in making good decisions about the inclusion, development and integration of new technologies in complex engineering projects [34]. The most widely used tool for readiness assessment is the Technology Readiness Level (TRL) scale [6]. The TRL scale was first developed at NASA in the 1970s [25] to be a consistent measure and a common understating of the state of development. The scale was originally devised to assist the transition from technology development to space mission development [39].

Following initial implementation within NASA in the '70s, the technology readiness concept was published again in 1989, as a 7-point scale [34]. In 1995, NASA published a refined 9-point scale, along with the first detailed descriptions of each level [4]. Today the TRL approach is being used in multiple industries and serves a similar purpose but in a broader context. Commercial implementations of the TRLs are similar to NASA's 9-point embodiment. Figure 1 shows a generic 9 scale TRL definition. The NASA scale begins with a technology in its very basic scientific form and progresses to a technology proven in the required

operating environment (Figure 1). Thus for a generic technology, the levels describe the demonstration requirements, including the environment and technology assembly status, gradually conforming to the final operating system as the design evolves.

Various definitions of "technology" exist at many different scales, namely components, modules of the system level. The predominant conceptualization within the TRL-community, at NASA, and used in this paper, is that of a component-technology. The TRL scale is used to assess the maturity of a component (or a principle that will eventually be embodied in a component) that features new materials, scale, or working principles.

The most widely used tool for the readiness assessment is the Technology Readiness Level (TRL) Scale. The TRL Scale was developed to support decision making in relation to the introduction of new technologies during the development of complex systems [24]. Although this scale has been used for decades, it does not reflect well the integration of new technological elements into the system architecture. Its application has other challenges related to system complexity, project planning, and subjectivity and imprecision of

the increasingly realistic testing. Once the technology is sufficiently proven, it can be incorporated into a system/subsystem.

The United States Department of Defence has adopted TRLs for all of its new procurement programs in 2001 [41]. A variety of industries have now generated customized standard guidelines for using TRLs for complex systems development, which includes USA Homeland Security [17], USA Department of Defence (Katz [19]), oil and gas, and infrastructure, e.g. DNV [12] and API [2], ABS[1] and UK Ministry of Defence [13, 19, 28 and 29], Nolte [32] and so on.

System architecture-related extensions to the TRL include Integration Readiness Level (IRL) and system readiness level (SRL), introduced by Sauser and his colleagues [15, 15 and 34 to 38]. Austin [3] provided an example of its application. Yasseri [42] has extended API adaptation of NSA’s TRL to include IRL and SRL. These reflect the reality that technologies do not exist in isolation, but rather they are connected through interfaces in the system architecture [45].

This paper differentiates between the system “readiness” and the system “maturity”. Following Smith [39] a distinction is made 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 [7], used “maturity” as part of the definition of “readiness” and thereby implied a relationship between the two terms. Other authors also used the terms interchangeably; e.g. See Azizian et al. [5].

Table 1 shows API’s definition of TRLs. A NASA-type TRL is also included alongside for the comparison purposes. Figure 2 shows a comparison of NASA and API scales.

Generally speaking, when a new technology is first invented or conceptualized, it is not suitable for the immediate application. Instead, new technologies are usually subjected to experimentation, refinement, and increasingly realistic testing. Once the technology is sufficiently proven, it can be incorporated into a system/subsystem. While technology and system development theoretically follow similar maturation paths, ultimately a technology is inserted into a system based on its maturity, functionality, and environmental readiness as well as its ability to integrate with the intended system.

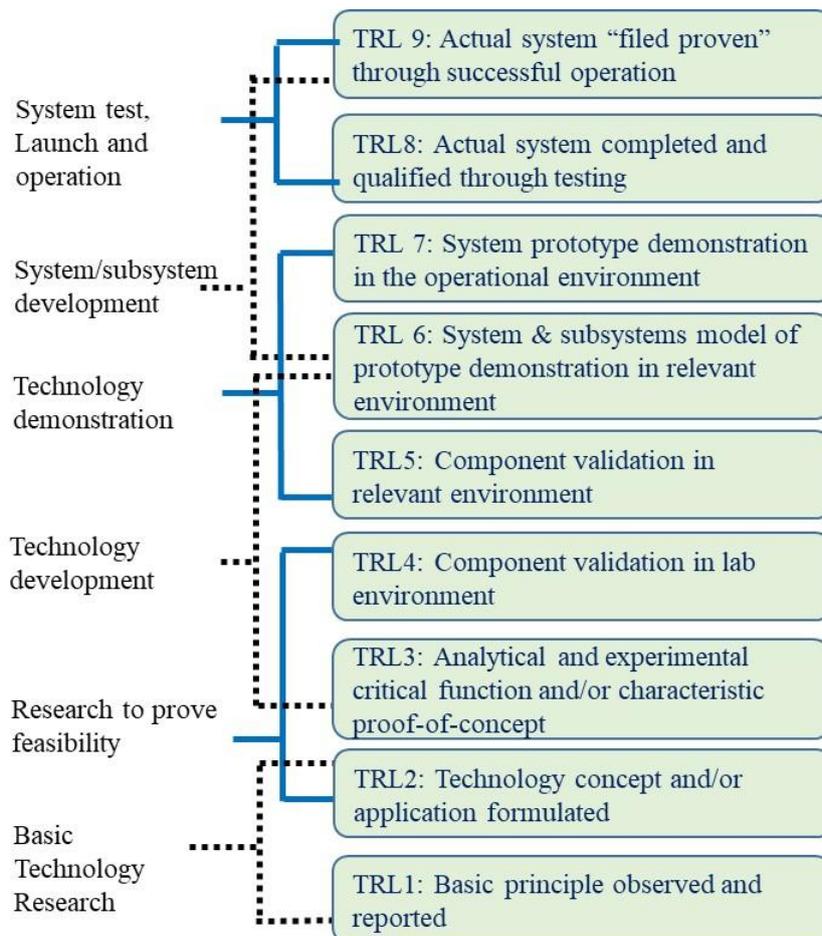


Figure 1: A generic NASA-type [32] TRL scale

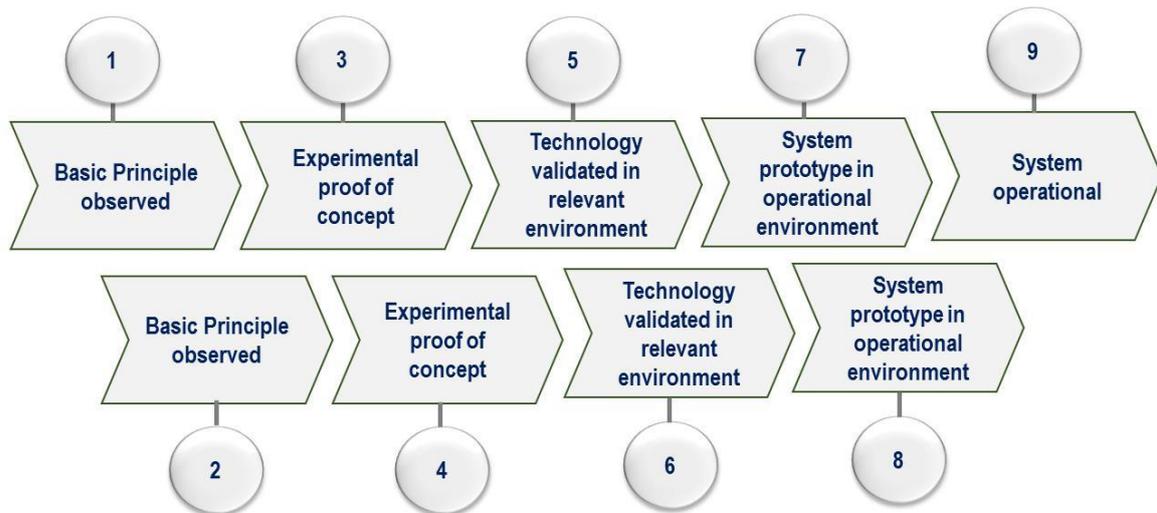
Table 1: API definition of TRLs and its equivalence with the NASA type [33] definition

	API 17N's TRL	API 17N's TRL	Development Stage Completed	Definition of the development stage	NASA Like TRL
Concept	initiation	0	Unproven Concept (Basic R&D, paper concept)	Basic scientific/engineering principles observed and reported; paper concept; no analysis or testing completed no design history.	1
{roof-of-concept	Concept	1	Proven Concept (As a paper study or R&D experiments)	a) Technology concept and/or application formulated b) Concept and functionality proven by analysis or reference to features common with/to existing technology c) No design history; essentially a paper study not involving physical models but may include R&D experimentation	2
	Proof-of-concept	2	Validated Concept (experimental proof of concept using physical model tests)	Concept design or novel features of the design is validated by a physical model, a system mock-up or dummy and functionally tested in a laboratory environment; no design history; no environmental tests; materials testing and reliability testing is performed on key parts or components in a testing laboratory prior to prototype construction	3
Prototype	Integration	3	Prototype Tested (System function, performance and reliability tested)	a) Item prototype is built and put through (generic) functional and performance tests; reliability tests are performed including reliability growth tests, accelerated life tests and robust design development test program in relevant laboratory testing environments; tests are carried out without integration into a broader system b) The extent to which application requirements are met are assessed and the potential benefits and risks are demonstrated	4
	Demonstration	4	Environment Tested (Pre-production system environment tested)	Meets all Requirements of TRL 3; designed and built as production unit (or full scale prototype) and put through its qualification program in simulated environment (e.g. hyperbaric chamber to simulate pressure) or actual intended environment (e.g. subsea environment) but not installed or operating; reliability testing limited to demonstrating that prototype function and performance criteria can be met in the intended operating condition and external environment	5
	commissioning	5	System Tested (Production system interface tested)	Meets all the requirements of TRL 4; designed and built as production unit (or full-scale prototype) and integrated into the intended operating system with a full interface and functional test but outside the intended field environment	6
Field qualified	Production	6	System Installed (Production system installed and tested)	Meets all the requirements of TRL 5; production unit (or full-scale prototype) built and integrated into the intended operating system; full interface and function test program performed in the intended (or closely simulated) environment and operated for less than three years; at TRL 6 new technology equipment might require additional support for the first 12 to 18 months	7
	Field proven	7	Field Proven (Production system has been field proven)	Production unit integrated into the intended operating system, installed and operating for more than three years with acceptable reliability, demonstrating a low risk of early life failures in the field	8 & 9

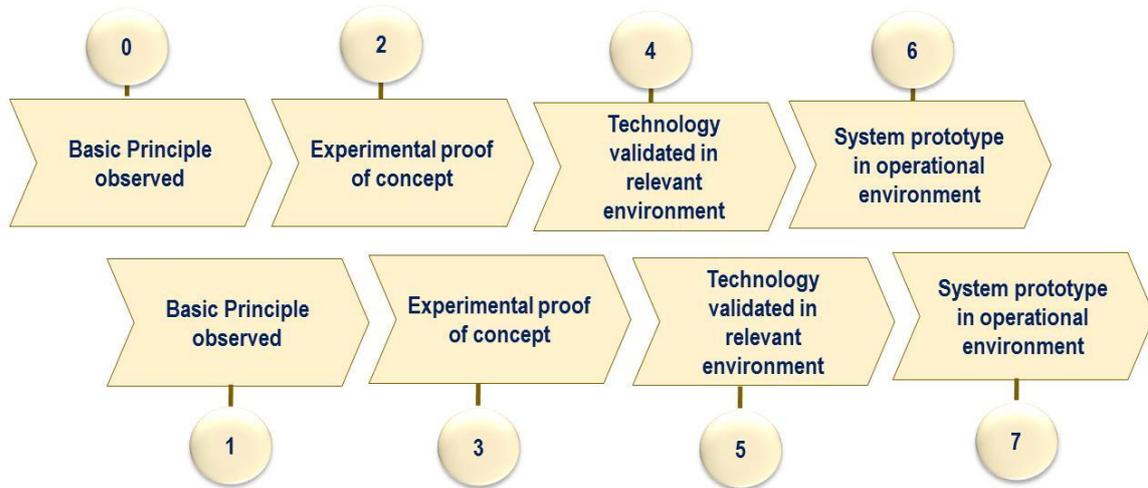
Achievement of API's TRL 4 [2] is one of several pieces of evidence that is used in the decision-making process in committing to the major capital investment [43]. Thus, the TRL 4 is critical for making the decision on whether to go forward with the investment. TRL 5 arguably is the most important stage (technically) during the subsea development process. At API's TRL 5 [2] 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 component level, it must consider testing of the assembly of components (or subsystems); testing at the quayside, and possibly in shallow water (i.e. a relevant environment) and/or the operational environment.

**A generic Technology Readiness Level**



**API 17N Technology Readiness Level**



**Figure 2: Comparison of NSA-type TRL scale with API's TRL scale**

TRLs provide a common understanding of the status of a technology in its development pathway, a means of assessing and managing risk, and decision making concerning funding and implementation of technology. As with any management tool, there are certain limitations to its use. The TRL approach has been used in different industries and has proved to be useful as a tool for:

- general understanding of technology status;
- risk indicator and management;
- decision making with respect to technology funding;
- Decision making with respect to technology insertion.

Assigning a TRL rank is not a quick task. These are some questions that need to be answered and backed by evidence. In the subsea context:

- Is technology (equipment) widely used by other operators?
- Is technology demonstrated in the final form (in a system somewhere in the world)?

- Is technology demonstrated in the relevant environment (field conditions)?
- What is the target performance/efficiency level (technically and economically)?
- What is currently achieved performance/efficiency?
- What are the materials involved and what is their availability?
- Is infrastructure available for deployment for this technology?
- What are the main barriers impeding the higher performance? ... etc.

**2. Systems Engineering V-Model**

TRL level is judged using the notion of Fit-For-Purpose (FFP), i.e. ready to use, supported by evidence gathered through analysis, simulation, experiment, standard testing and in-service experience. It is important to state both purpose and application; since mature irrelevant technology is as useless as immature relevant technology. Readiness only has a meaning in relation to the purpose of the product or service.

The systems engineering framework can help to document and track all requirements which are the system purposes. Systems Engineering is an integrative process of top-down synthesis, development, and operation of a real-world system that satisfies, in a near optimal manner, the full range of requirements for a system. [48 and 49]

The system engineering V-model describes the activities and results that must be produced during development (Figure 3). The left side of the V represents the system specification stream, where the system requirements and the system and subsystem or component designs are specified. The designed components are then fabricated and installed at the bottom of V. Component fabrication is followed by the testing stream on the right tail of the V, where the gradually evolving and growing system is verified against specifications defined on the right-hand side of the V.

The system is specified top-down and then the subsystems are integrated bottom up. Additionally, the definition of distinct steps for the design, at different hierarchy levels, appears first in the V-model and enables breaking down of the system into independent subsystems. The system is decomposed (broken down) into functional subsystems, which are easier to handle. Subsystems can then be designed and fabricated in parallel, according to the system specifications defined in the previous phase.

Technology readiness only has a meaning in relation to the purpose of the system that will be using it. If something does the job for which it is designed then it is ready for insertion.

Describing the purpose of a system, one needs to look beyond the system itself, and into the activities that it will support. For example, the purpose of a banking system is not to be found in the technology used to build it, but in its day-to-day business activities in fulfilling the needs of its customers. Thus, requirements are a set of activities concerned with identifying and communicating the purpose of a system and the contexts in which it will be used. Requirements act as a bridge between the real-world needs of the Client, and the capabilities and opportunities afforded by technologies. Then the technology is assessed if it would support the requirements.

Requirements analysis provides a process for understanding the purpose of a system and the contexts in which it will be used. It bridges the gap between, an initial vague recognition that there is a need, and the task of building a system to address such a need. Ideally, each requirement from the highest to the lowest level of the project must link to a parent requirement. Requirements without parents will either represent a nice to have or a missing requirement at the higher level. If it is the former, the existence of the requirement must be carefully considered again. In the event of the latter, the requirement needs to be rolled back up to ensure completeness of the requirements at the higher level. A simple trace matrix can be used to simplify and provide a clearer arrangement of the traceability and is needed to ensure that all higher-level requirements are linked to the lower level requirements, and will be maintained throughout the system development. This is one of several parameters which influences the TRL decision.

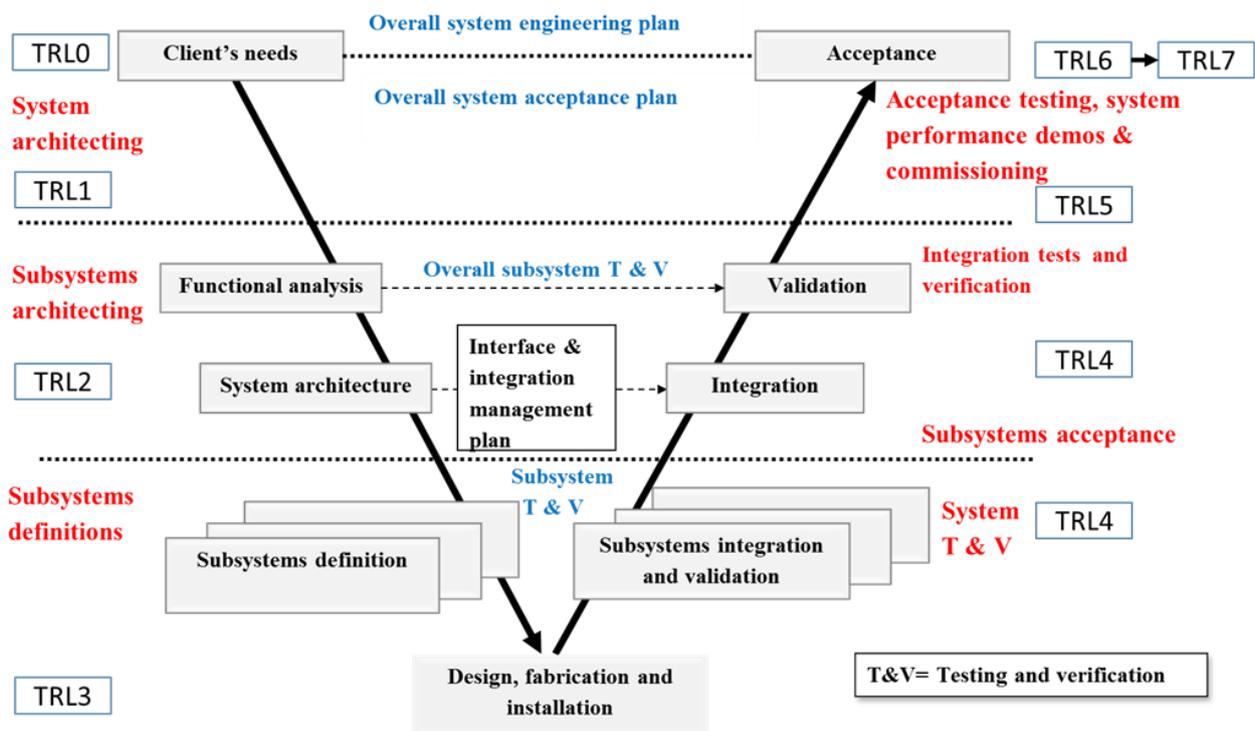


Figure 3: Systems engineering V-model for product development.

The traceability requirement ensures that all a system’s needs can be traced to one or more piece of equipment, as well as all equipment can be traced to a requirement. Thus the traceability references the link between user requirements, specifications and test cases. This makes it possible to trace cross-references between specified elements.

**3. Integration Readiness Level (IRL)**

The TRL scale is component oriented. Namely, the focus of TRL is on individual technologies (components) in isolation, as the primary use of the TRL scale is to align different technological developments and move them along the same timeline. However, the higher TRLs (e.g. API’s TRL 6: installation completed and the system being qualified i.e. validated), are about integrating different individual technologies, possibly with different maturities, into a complex system. Acceptable technology maturity has often been the principal driver, particularly in systems where availability is fundamental to the customer requirements. While TRL provides a metric for describing components’ maturity status, one should still be interested in a metric that provides a description of integration, i.e. how components relate to each other. It is vital that all stakeholders have the same understanding when evaluating the integration maturity, which also can be used together with TRL to potentially determine the system readiness.

Many authors extended the TRL classifications to account for the effects of having to integrate multiple technologies to create a single system; see e.g. Sauser et al [34] and Yasseri [43]. They introduced another metric called Integrated Readiness Level (IRL) to compliment the TRL metric for the integration of applications. They also developed a protocol to measure the overall technological readiness of a system, System Readiness Level (SRL), by combing the TRL and IRL metrics of all technologies included in the system to produce an index to measure the complete system readiness. Yasseri [43 and 47] created an Integration Readiness Level (IRL) for subsea systems to measure integration maturity on a scale similar to API’s TRL [2] with the objective that it could be combined with TRL to provide a system-level readiness. Assessment of the readiness of the individual technologies will contribute to risk reduction in budgets and planning. Other readiness assessment metrics have been developed to compliment TRL, see for example London et al [22] and McConkie [27]

Further clarification of the eight levels of IRL (including zero) is presented in Figure4. From Table 2 can be understood as having three stages of integration definition: semantic, syntactic, and pragmatic. Semantics is about relating meaning with respects to clarity and differentiation. Thus IRL 0-2

**Table 2: Definitions of TRL, IRL and SRL**

Phase	TRL	Development stage	IRL	Development stage	SRL	Development stage
System validation	7	Proven in the field - Production system field-proven.	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 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 - Preproduction 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 R&D experimentation.	1	There is some level of specificity to the system functionality to allow identification of linkage between technologies.		Concept Refinement. Two or more competing concept being considered.
	0	Unproven concept - Basic research and development (R&D) in papers.	0	The interface, i.e. the linkage, between technologies can be identified/characterised with sufficient clarity.	0	Concept Definition. Various ideas are being considered or discounted

are considered fundamental to describing what we define as the three principles of integration: i.e. interface, interaction, and compatibility. It can be contended that these three principles are fundamental to an integration effort. The next stage is Syntactic, which is defined as a conformance to rules, where IRLs 3-5 are about the assurance that an integration effort is in compliance with specifications. The final stage is Pragmatic, which relates to practical considerations. Thus, IRLs 6-7 are about the assertion of the application of an integration effort.

**4. Systems readiness level**

The application of an IRL in the assessment process provides a check as to where the technology maturity is on an integration readiness scale. Just as a TRL has been used to assess the risk associated with developing technologies, an IRL is designed to assess the risks associated with integrating these technologies. Table 2 defines an SRL scale that incorporates the maturity level of components and the interoperability of the entire subsea system, including integration with its environment.

Sausser et al [34] combined the TRLs and IRLs for a system under development, using a matrix multiplication. Yasseri [43] proposed a methodology to aggregate TRL and IRL into a single metric, termed  $SRL_{est}$ . This methodology requires all components to be assessed using TRL (Table 2), as well as their readiness for integration with each other and the environment to be assessed using IRL (Table 2). For more detail see [43]. The proposed method combines TRLs and IRLs into a single composite metric, yielding a numerical value between 0 and 7. The estimated  $SRL_{est}$  is used in Table 2 to judge system readiness, compared with what it should be at the time of

assessment. Building a spreadsheet (see the case example) will enable the user to regularly review the state of system readiness and track the project’s progress.

**5. Domain Mapping**

A system is described as an aggregation of equipment and enabling products to achieve a given purpose. In the context of an oil and gas production system, these are the subsystems and facilities that together achieve the mission. A system can be mapped in different ways depending on the overall goal. It may show a system as a single facility or several facilities linked together. It is this diagram that provides a visual tool for applying TRL. Thus, it is necessary to construct a system map to determine the overall purpose and identify all equipment in a facility that is required to create a complete production system. A system map shows every piece of equipment that is required, 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 equipment of the system, emphasizing their interconnection paths while omitting all physical details. In an electronic circuit diagram, the layout of the symbols may not resemble the layout in the circuit. The schematic (see below) shows the intent and how the parts are supposed to interact with each other. Thus, a schematic, or schematic diagram, is a representation of the elements of a system using abstract graphic symbols rather than realistic pictures. A schematic usually omits all details that are not relevant to the information. In contrast, a construction drawing shows things as they are actually laid out, and shows them to scale. A construction drawing can be used to build the system.

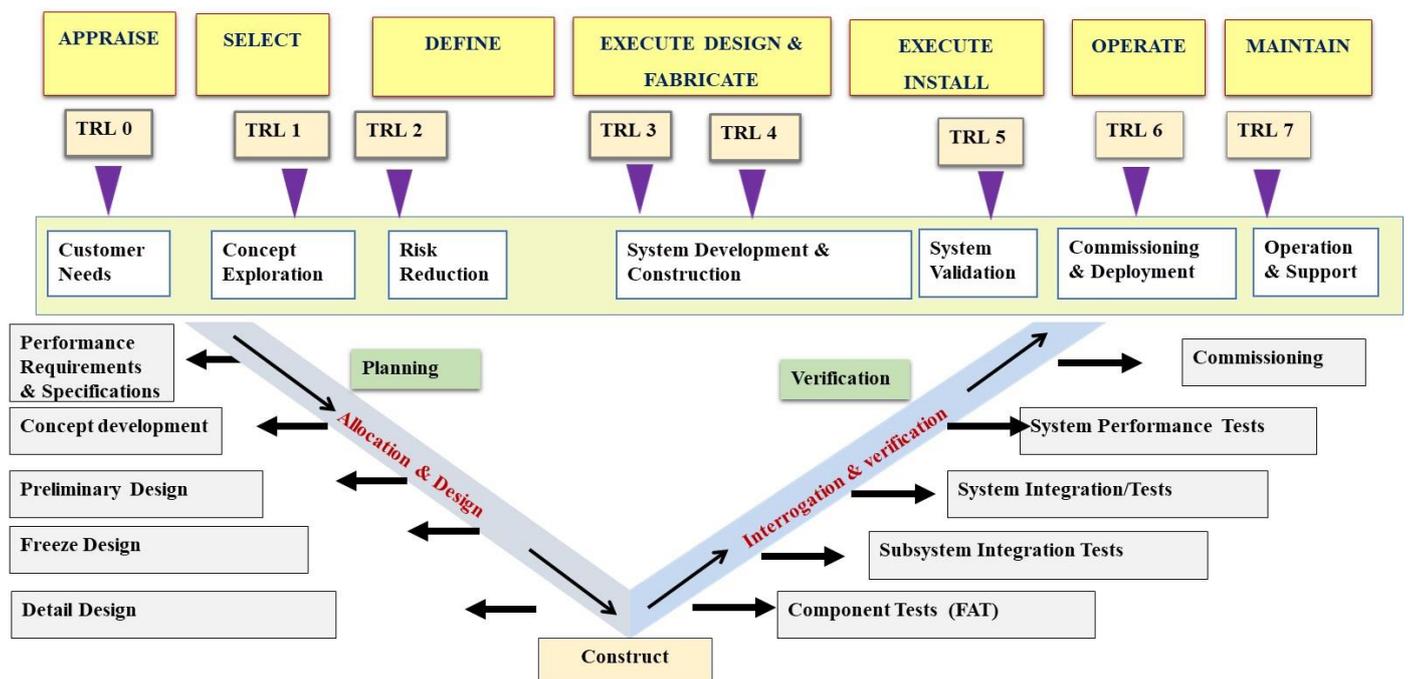


Figure 4: Timeline for stage-gating in a subsea development

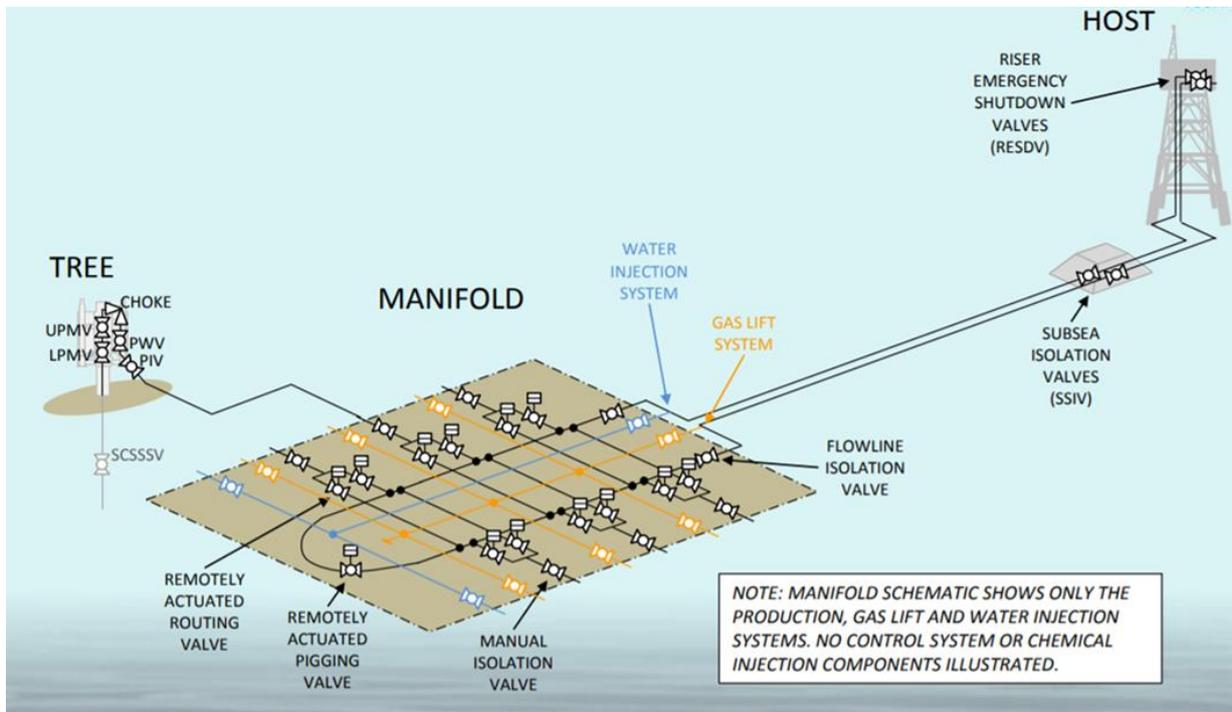


Figure 5: A schematic of a subsea production system

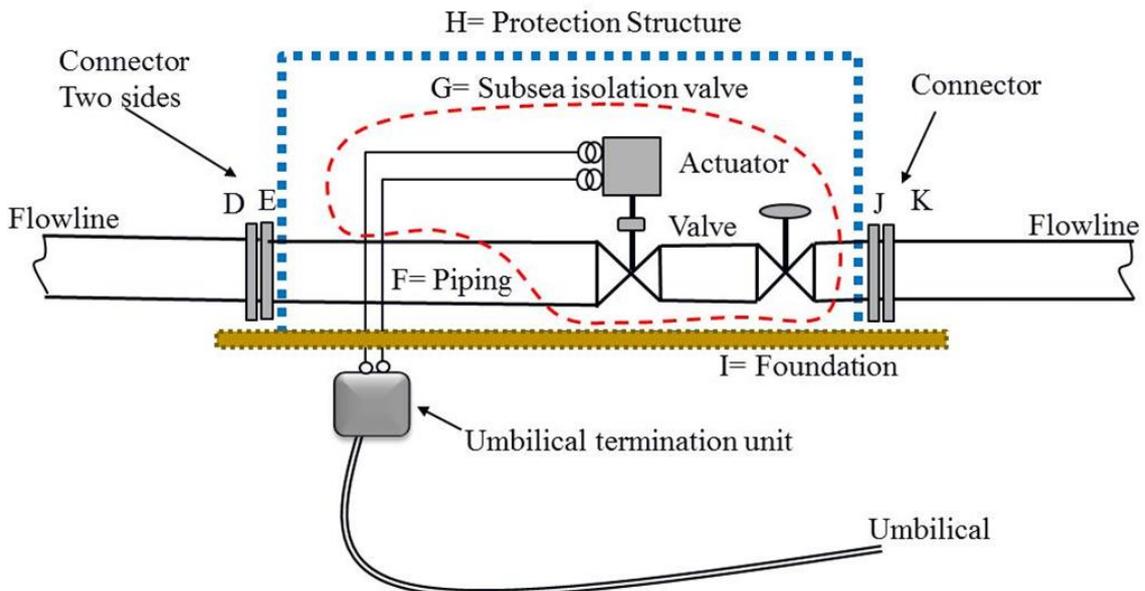


Figure 6: A detailed schematic of the SSIV used in the SPS system shown in Figure 5 above.

Figure 5 shows a schematic of a simple subsea production system. A schematic of the subsea isolation valve (SSIV) shown in Figure 5 is shown in more detail in Figure 6. SSIV components have been labelled for later use in this paper.

Two popular methods of representation of a system functional architecture (or alternatively its structural elements) are the Block Diagram (BD) and the Design Structure Matrix (DSM) as further described below.

**Block Diagram:** A method to avoid unnecessary clutter is the Block Diagram. A Block Diagram is a representation of a system in which the principal or functions (or parts, or equipment) are represented by blocks connected by lines that show the relationships

between the blocks. They are used in various engineering disciplines e.g. in reliability analysis, and process flow diagrams. A Block Diagram will not show every detail. Block Diagrams are typically used for higher level, less detailed descriptions that are intended to demonstrate overall concepts without concern for the details of implementation. As such, they provide a quick, high-level view of a system to rapidly identify points of interest or trouble spots. The Block Diagram is especially focused on the input and output of a system. It cares less about the internal workings. This principle is referred to as the Black Box in engineering, whereby the parts that get from input to output are unknown, or they can be left for a later in-depth study.

Figure 7 shows the Block Diagram of a simple system consisting of 7 components grouped into 2 modules at an advanced stage of the development. There are interfaces between the components of each module, as well as between components of the two modules. Interfaces between the two components are shown by double-headed arrows, which implies, that the readiness of two components to be integrated is interdependent. The arrow is not intended to indicate the direction of the flow, but to show dependency or relationship. This is a simple representation of a system architecture, which captures the relationship between different components.

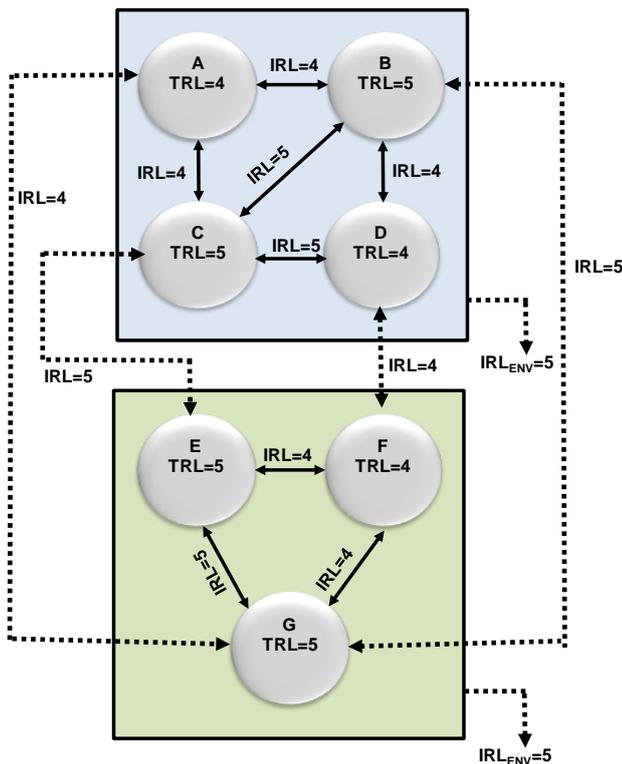


Figure 7: A system consisting of two modules

**Design Structure Matrix:** DSM is a visual tool [11] that represents the relationships and dependencies between components of a system. The component-based DSM (Eppinger and Browning, [14]), which is used in this paper, comprises of a list of components in some desirable order whereby upstream components are listed in the upper row. DSM is a square matrix for a visual representation of a system ([42], [9] and [10]), which shows both components of the system and linkages between them. It is the equivalent of an adjacency matrix in graph theory and is used in systems engineering and project management to model the structure of complex systems, in order to perform system analysis, project planning and organizational design. The system elements are often labelled and are shown in a row of the matrix and in a column on the left of the matrix. These elements represent subsystem, components (in a component-based DSM), or project activities (in an activity-based DSM).

Figure 8 shows a directed graph network and its representation using DSM is shown in Table 3. Figure 8 depicts the functional block diagram which gives a view of the functional elements, and how they must interface to achieve the overall goal (relationships). The components are shown as rows and columns in the matrix (Table 3) where they are listed in the same order along both axes. An off-diagonal mark located within the matrix denotes a coupling between two components (relationship). Table 3 shows that components C and H do not require input from the other components, but A, B, D, E, F, and G do receive inputs. The component interactions are represented by “X” marks in the off-diagonal cells. The marked cells indicate dependencies between components. Reading down a column indicates that a component provides input to others in its associated row. On the other hand, a component in the row receives input from the component in the corresponding column when reading across a row in the matrix. A number can be used instead of “X” to represent some sort of quantity, for example, risk or/and the volatility of the interface (see [44]).

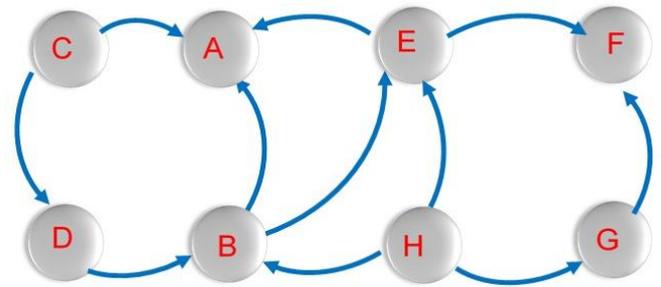


Figure 8: A directed graph network showing component of a system and their connectivity

Table 3: DSM of the directed graph network shown in Figure 7. Reading along a row reveals the input/dependency which is marked by an X placed at the intersection of that row with the column that bears the name of the component providing input.

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

Since the network shown in Figure 7 is a directed graph, its DSM shown in Table 3 is an asymmetrical matrix. This paper, for simplicity, assumes at the highest level of system hierarchy all dependencies are a two-way relationship; thus, leading to a symmetrical matrix. The relationship maps show that element D is dependent on C through some characteristic of D. In doing this, the analyst should understand better the

complexity of a system and, in turn, has more information to manage dependencies and use this information to improve system performance and manage interfaces between the elements [14]. As another example, the Block Diagram of Figure 6 is mapped into the Design Structure Matrix (DSM) as shown in Table 4. Here it is assumed that dependency is bilateral, thus the DSM is a symmetric matrix. The DSM maps the elements of a system to each other (like a two-way table), enabling concise representation and integration analysis. Reading across a row of the matrix shows where the element in that row sends its outputs and reading down a column shows where the element in that column receives its inputs [9].

**Table 4: DSM representation of the subsea isolation valve shown in Figure 5. Note the symmetric matrix due to the assumption of two-way mutual dependency.**

Components		D	E	F	G	H	I	J	K
Connectors (female)	D	D	X						
Connectors (male)	E	X	E	X					
Piping	F		X	F	X	X		X	
SSIV	G			X	G				
SSIV Structure	H			X		H	X		
SSIV Foundation	I					X	I		
Connectors (female)	J			X				J	X
Connectors (male)	K							X	K

The X marks in Table 4 indicate the existence and direction of information flow or a dependency of one component with another. Reading along a row reveals the input/dependency flows by an X mark placed at the intersection of that row with the column that bears the name of the input task. Reading down a column reveals the output information flows from that component to another component by placing an X in a similar manner as described above. For example in the DSM (Table 4), the marking in row E and column D indicates a dependency between E and D (E must integrate with D). The cells on the diagonal are typically used to represent the system elements and their interface requirements. Marks below the diagonal represent forward flow of information, and marks above the diagonal represent feedback from a later downstream task to an earlier or upstream one. This means that the earlier task has to be repeated in light of the late arrival of new information, thus making the processes iterative. Design iterations create rework and require extra communications and negotiation. Matrix-based tools provide some insight into the internal relationship of a complex system (i.e. a dependency map and their complexity); however, they do not expose the logic behind these dependencies. That is, if component A is shown to relate to component E, it is not clear why and how this relationship exists

and where it originates from. Such information can be represented on Block Diagrams.

**Table 5: DSM for the system shown in Figure 7. Components A to J are mapped along the diagonal and off-diagonal numbers are the IRL values.**

	TRL		A	B	C	D	E	F	G	ENV
M1	4	A	A	4	4				4	
	5	B	4	B	5	4			5	
	5	C	4	5	C	5	5			
	4	D		4	5	D		4		4
M2	5	E			5		E	4	5	
	4	F				4	4	F	4	
	5	G	4	5			5	4	G	4
ENV										

As another example, the Block Diagram of Figure 7 is mapped into a DSM matrix (Table 5). The TRL of each component is shown in the column to the left of the components. Numbers in off-diagonal terms are the IRL of this system which consists of only two modules. The decision regarding the level of detail required for a system map will be dependent on the technologies being developed. In many cases a tiered approach will be required, starting with a super-system diagram and then a system diagram for individual plants or facilities; possibly linked together. In some cases, (e.g. for complex, highly integrated equipment), sub-system diagrams may be required to highlight aspects of a piece of equipment within an assembly of the system that requires development. Generally presenting every component of a system in a single matrix obscures its visual usefulness. A subsea system can be organised into a hierarchical structure, e.g. subsystem, sub-subsystems and assemblies or components ([44]). Such hierarchical representation avoids problems related to presenting extremely large matrices by shifting the focus to various levels in the hierarchy at a time, which enables the analysis of a system at different levels of details as necessary. In general, the DSM analysis only looks at relationships across components (at the same level) and not within components (which is the next level below).

### 5. Example Case

A system is a collection of equipment and enabling software linked together to achieve a given goal. Figure 9 shows an example system consisting of three subsystems (or modules) linked together. Within each subsystem, there are a number of components or items and it is to them that the TRLs are applied.

A process which is known as Technology Readiness Assessment (TRA) is used to identify Critical Technological Elements (CTEs) of a system. The TRA is a systematic, evidence-based process [46] that assesses the maturity of CTEs. A technological element is “critical” if the system depends on it to meet

operational requirements. Thus, if a system depends on specific technologies to meet operational threshold requirements in development, production, and operation, and if the technology is new, that technology is deemed to be Critical Technological Element (CTE). Not every component is subjected to a rigorous TRA assessment.

One should make a distinction between critical technology and necessary technology. In principle, every equipment in a system is necessary since if there is no need for an equipment, it can be eliminated. However, only a few pieces of equipment may be critical, since there is no substitute 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;

namely, every equipment is considered to be critical. The level of detail is decided by the assessor(s), drawing 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.

Table 6 shows a DSM for the case example of Figure 9. Simplifications can be made to prevent DSM clutter. In practical cases, this matrix can be much larger. However, one should only include important items and avoid unnecessary complications, since including every nut and bolt would not lead to a better conclusion. Once the system's DSM (Table 6) is complete, TRLs for each item can be assigned by following the description in Table 1.

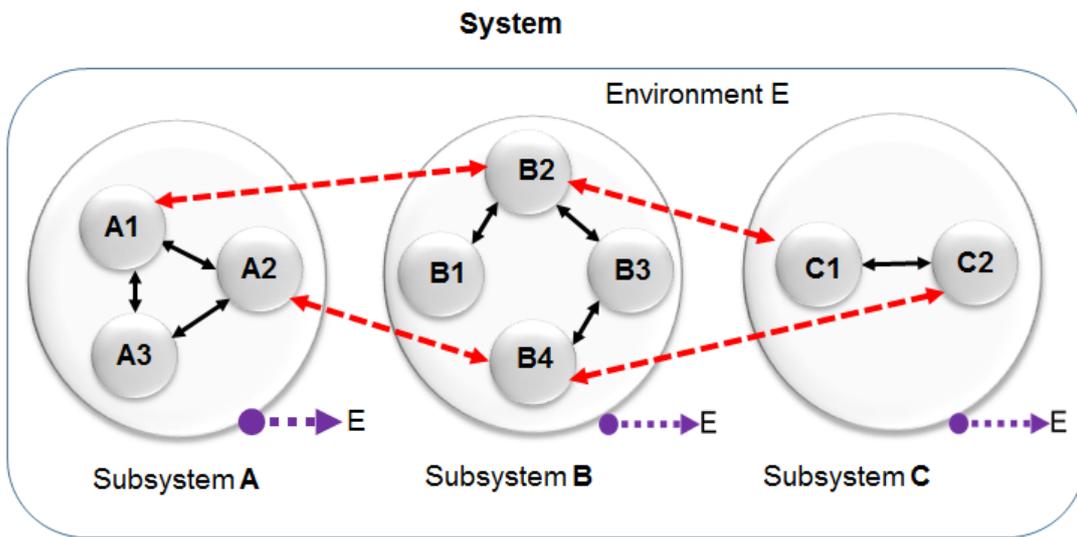


Figure 9: System architecture of the case example.

Table 6: A DSM of case example shown in Figure 9.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17		
2			Components															
3			A1	A2	A3	B1	B2	B3	B4	C1	C2	ENV						
4		TRL	IRL Matrix										Ave. IRL	TRL*Ave_IRL	SQRT	Module IRL		
5	A1	5	4	4	5		5						4.67	23.33	4.83			
6	A2	4	4	4	4				4				4.00	16.00	4.00			
7	A3	4	5	4	4							4	4.33	17.33	4.16	4.35		
8	B1	5			4		4						4.00	20.00	4.47			
9	B2	5	5				4	4	4		5		4.50	22.50	4.74			
10	B3	4					5	4	4		4		4.33	17.33	4.16	4.39		
11	B4	4		4				4	4		5		4.33	17.33	4.16			
12	C1	5					5				5		5.00	25.00	5.00			
13	C2	5						4	5		5		4	4.67	23.33	4.83	4.92	
14																SRL=	3.44	

For this example, it is assumed that two interfacing components could be at a different TRL, but their integration readiness levels are the same and equal to the least ready component, (due to mutual dependency), hence yielding a symmetric matrix. In general, if two components are combined to create an assembly, there may be different degrees of integration

readiness for each component and hence the matrix may not be symmetric in some cases. Symmetry assumption is not necessary for the application of the method.

Each row of the column "Average\_IRL" in Table 6 is the arithmetic mean of all IRLs in that Row, determined by summing up of IRLs of all interfaces

across the row and dividing it by the number of interfaces; e.g. for the first row  $(4 + 5 + 5)/3 = 4.67$ . The 15<sup>th</sup> column gives the results of multiplication of the component's TRL by the average of its IRLs; e.g., in Row 1:-  $5 \times 4.67 = 23.33$ . The 16<sup>th</sup> column gives the square root of the 15<sup>th</sup> Column, which is SRL of each component. In statistics and its applications, the **root-mean-square** (abbreviated **RMS** or **rms**) is defined as the square root of the mean square (the arithmetic mean of the squares of a set of numbers). The RMS of the 16<sup>th</sup> column is given in Column 17, which is the SRL for each module, giving a composite *module* readiness index. For the first subsystem [43]:

$$M_{1-R} = \sqrt{\frac{23.33 + 16.00 + 17.33}{3}} = 4.35$$

Three in the denominator is the number of components of the first subsystem. Alternatively,

$$M_{1-R} = \sqrt{\frac{(4.83)^2 + (4.00)^2 + (4.16)^2}{3}} = 4.35$$

An estimate of the system readiness level is given by [43]

$$SRL_{estimate} = \sqrt{\frac{4 \times (4.83)^2 + 4 \times (4.00)^2 + 4 \times (4.16)^2}{7 \times 3}} = 3.44$$

Where, 7 is the highest score in API's TRL ranking [2] and it is used for normalisation purpose.

From a metric point of view both  $SRL_{est}$  and SRL are meant to measure the same things on the same scale. However, SRL is defined (Table 3), while  $SRL_{est}$  is derived by aggregation of attributes of all components. The estimate of system readiness reaches its highest level from below, as it measures the system readiness as a whole, not its elements. If all components mature simultaneously along the same path, then  $SRL_{est}$  reaches SRL.

Using a value of 3.44 in Table 1, the system must be at assembly and installation stage, if the project schedule dictates a different level then reasons must be sought. One should distinguish between component readiness level and the system readiness level. For instance, a component is investigated if it had achieved TRL 6. Although this investigation is in the context of the intended system in its environment, the focus is on that individual component, not the whole system.

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

## 6. Concluding Remarks

In a previous paper by the lead author [43] two new metrics were defined to complement API's TRL scale, I.e. IRL and SRL. The 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, which combines Technology Readiness Level (TRL) with IRL quantitatively into a system readiness metric. The methodology is further extended by adding a system engineering framework around the process to track the progress of a subsea system development. The process of estimating SRL is described using a case study, which is a simplified version of the development of an actual subsea subsystem.

Comparing the estimated SRL and values in the SRL table given in this paper would indicate the level of system readiness. These three indices can provide part of the required information for the sanction bodies to allow a project to move through the review gate to the next phase of development, in a stage-gate process [44]. Technology development, Integration and Systems development follow similar evolution (or maturation) paths, TRL, IRL and SRL are not generally far apart, allowing performing arithmetic on the ordinal numbers [47]. This paper distinguishes readiness from maturity. If a technology is used in another system then it is matured, but it is considered not ready for the system under development until proven so. Thus, an existing mature technology enters into a new system at TRL 5 or 6 at best.

The proposed System Readiness Assessment methodology provides decision-makers with a snapshot of a system's holistic state of readiness, and quantifies the level of component-to-component integration during the system development, helping to improve design, fabrication and installation management. Implementation of the SRA methodology aids decision makers in identifying both programmatic and technical risk areas.

## 8. REFERENCES

1. ABS, (2017). Guidance notes on Qualifying New Technologies, American Bureau of Shipping, PP 45
2. API Recommended Practice 17N (2009), Recommended Practice for Subsea Production System Reliability and Technical Risk Management.
3. Austin, M. F., & York, D. M. (2015). System Readiness Assessment (SRA) an Illustrative Example. *Procedia Computer Science*, 44, 486–496. <https://doi.org/10.1016/j.procs.2015.03.031>
4. Azizian, N. Sakami, sh. and Mazzuchi.T. (2009). "A Comprehensive Review and Analysis of Maturity Assessment Approaches for Improved Decision Support to Achieve Efficient Defense Acquisition, Proceedings of the World Congress on Engineering and Computer Science 2009 Vol II WCECS 2009, October

- 20-22, 2009, San Francisco, USA, [http://www.iaeng.org/publication/WCECS2009/WCECS2009\\_pp1150-1157.pdf](http://www.iaeng.org/publication/WCECS2009/WCECS2009_pp1150-1157.pdf)
5. Azizian, N., Mazzuchi, T., Sakami, Sh. and David F. Rico D. (2011). A Framework for Evaluating Technology Readiness, System Quality, and Program Performance of U.S. DoD Acquisitions, *Systems Engineering* Vol.14, no. 4: 410-26.
  6. Bakke, Kjersti (2017), Technology readiness levels use and understanding, Master thesis, University College South-East Norway, last accessed 31/05/2018 <https://brage.bibsys.no/xmlui/handle/11250/2452831>
  7. Bilbro J.W. (2007). A Suite of Tools for Technology Assessment. In *Technology Maturity Conference: Multi-Dimensional Assessment of Technology Maturity*. Virginia Beach, VA: AFRL. <http://www.dtic.mil/cgi-bin/GetTRDoc?AD=ADA507181>.
  8. Bissell C. and Chapman D. (1992). *Digital Signal Transmission*. Cambridge University Press. UK
  9. Browning, T. (2001). Applying the Design Structure Matrix to System Decomposition and Integration Problems: A Review and New Directions, *IEEE Transactions on Engineering Management*. 48(3):292-306, 200.
  10. Browning, T. (2002). Modelling Impacts of Process Architecture on Cost and Schedule Risk in Product Development, *IEEE Transactions on Engineering Management*. 49(4), pp 428-442.
  11. Browning, T.R. (2016). Design structure matrix extensions and innovations: a survey and new opportunities, *IEEE TRANSACTIONS ON ENGINEERING MANAGEMENT*, VOL. 63, NO. 1, February 2016.
  12. DNV-RP-A203 (2011). *Qualification of new technology*. Det Norske Veritas, Høvik, Norway.
  13. Dowling, T. and Pardoe T. (2005). *TIMPA - Technology Insertion Metrics*, Volume 1, Ministry of Defence, United Kingdom, QinetiQ.
  14. Eppinger, S.D. and Browning, T.R. (2012). *Design Structure Matrix Methods and Applications (Engineering Systems)*, MIT Press, 19-Jun-2012, 280 pages. ISBN-10: 0262017520 DoD, Director, Research and Engineering (DDR&E), "Technology Readiness Assessment (TRA) Deskbook", July 2009, Appendix F.
  15. Gove, R. (2007). *Development of an Integration Ontology for Systems Operational Effectiveness*, Department of Systems Engineering and Engineering Management, Stevens Institute of Technology, Hoboken.
  16. Gove, R., B. Sauser, and J. Ramirez-Marquez. (2007). *Integration Maturity Metrics: Development of an Integration Readiness Level*. In Stevens Institute of Technology, School of Systems and Enterprises Hoboken, NJ: SSE\_S&EM\_004\_2007.
  17. Homeland Security Institute, (2009), "Department of Homeland Security Science and Technology Readiness Level Calculator (ver 1.1) Final Report and User's Manual," Jesus, G.T. and Chagas, M.F. (2018). *Integration Readiness levels Evaluation and Systems Architecture: A Literature Review*, *International Journal of Advanced Engineering Research and Science (IJAERS)*, Vol-5, Issue-4, pp73-84.
  18. Kujawski, E. (2010). The trouble with the System Readiness Level (SRL) index for managing the acquisition of defense systems National Defense Industrial Association 13th Annual Systems Engineering Conference October 25-28, 2010, San Diego.
  19. Katz, D.R., Sakami, S., Mazzuchi, T., and Conrow, E.H., (2015), "The Relationship of Technology and Design Maturity to DoD Weapon System Cost Change and Schedule Change During Engineering and Manufacturing Development," *Syst. Eng.*, vol. 18, no. 1, pp. 1–15.
  20. Institute of Electrical and Electronics Engineers - IEEE, International Electrotechnical Commission - IEC, & International Organization for Standardization - ISO. (2007). *ISO/IEC 26702-2007 IEEE 1220-2005 Standard for Systems Engineering - Application and Management of the Systems Engineering Process*. Geneva, Switzerland: ISO/IEC/IEEE. <https://doi.org/10.1109/IEEESTD.2007.386502>
  21. ISO 16290:2013, (2013). *Preview Space systems -- Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment*. Pp 12.
  22. London, M. A., Holzer, T. H., Eveleigh, T. J., & Sakami, S. (2014). Incidence matrix approach for calculating readiness levels. *Journal of Systems Science and Systems Engineering*, 23(4), 377–403. <https://doi.org/10.1007/s11518-014-5255-8>
  23. Lord, F.M. (1953). on the statistical treatment of football numbers, 1953, *American Psychologist*, 8, 750-751, [http://www.stat.wharton.upenn.edu/~hwainer/Readings/Frederick%20Lord\\_On%20the%20statistical%20treatment%20of%20football%20numbers.pdf](http://www.stat.wharton.upenn.edu/~hwainer/Readings/Frederick%20Lord_On%20the%20statistical%20treatment%20of%20football%20numbers.pdf)
  24. Mankins, J. C. (1995). *Technology Readiness Levels*. Washington, USA, <https://doi.org/10.1080/08956308.2010.11657640>
  25. Mankins, J. C. (2009). *Technology readiness assessments: A retrospective*. *Acta Astronautica*, 65(9–10), 1216–1223. <https://doi.org/10.1016/j.actaastro.2009.03.058>
  26. Mankins, J. C. 2002. *Approaches to Strategic Research and Technology (R&T) Analysis and Road Mapping*. *Acta Astronautica* 51 (1-9): pp. 3
  27. McConkie, E., Mazzuchi, T., Sakami, S., Marchette, D. (2013). *Mathematical properties of System Readiness Levels*. *Systems Engineering*, v 16, n 4, p 391-400.
  28. MoD. UK Ministry of Defence, (2008) "System Readiness Levels (SRLs)", AOF Technology Management Policy, Information and Guidance on the

- Technology Management aspects of Defence Acquisition version 1.0.1, available at: [http://www.aof.mod.uk/aofcontent/tactical/techman/content/srl\\_whatarethey](http://www.aof.mod.uk/aofcontent/tactical/techman/content/srl_whatarethey). Last accessed 10/10/2012.
29. MoD. UK Ministry of Defence, (2011). Defence Technology Strategy for the Demands of the 21st Century, [http://www.mod.uk/nr/rdonlyres/27787990-42bd-4883-95c0-b48bb72bc982/0/dts\\_complete.pdf](http://www.mod.uk/nr/rdonlyres/27787990-42bd-4883-95c0-b48bb72bc982/0/dts_complete.pdf). Last accessed 12/10/2012.
30. NASA, (2007), NASA Systems Engineering Handbook, Washington, D.C.
31. The NASA technology push towards future space mission systems. *Acta Astronautica*, 20, 73–77. [https://doi.org/10.1016/0094-5765\(89\)90054-4](https://doi.org/10.1016/0094-5765(89)90054-4)
32. Nolte, W. L., Kennedy, B. M., & Dziegiel, R. J. J. (2003). Technology Readiness Level Calculator. White Paper: Air Force Research Laboratory, 2004. <http://www.dtic.mil/ndia/2003systems/nolte2.pdf>
33. Olechowski, A. L., Eppinger, S. D., & Joglekar, N. (2015). Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities. In Portland International Conference on Management of Engineering and Technology (PICMET). Portland, USA: IEEE. <https://doi.org/10.1109/PICMET.2015.7273196>
34. Sauser, B., J. Ramirez-Marquez, D. Henry, D. Dimarzio, and J. Rosen. 2007. Methods for Estimating System Readiness Levels. The School of Systems and Enterprises White Paper. Hoboken NJ: Stevens Institute of Technology.
35. Sauser, B., J. Ramirez-Marquez, R. Magnaye, and W. Tan. 2008. System Maturity Indices for Decision Support in the Defense Acquisition Process. In 5th Annual Acquisition Symposium. Monterey, CA.
36. Sauser, B., D. Verma, and J. Ramirez-Marquez. (2006). From TRL to SRL: The Concept of Systems Readiness Levels. In Conference on Systems Engineering Research. Los Angeles, CA.
37. Sauser, Brian, Jose Ramirez-Marquez, D. Henry, and D. Dimarzio. (2008). A System Maturity Index for the Systems Engineering Life Cycle. *International Journal of Industrial and Systems Engineering* 3.
38. Sadin, S. R., Povinelli, F. P., & Rosen, R. (1989).
39. Smith, J. D. (2005). An Alternative to Technology Readiness Levels for Non-Developmental Item (NDI) Software. Proceedings of the 38th Annual Hawaii International Conference on System Sciences. <https://www.computer.org/csdl/proceedings/hicss/2005/2268/09/22680315a.pdf>
40. Stevens, S. S., (1946). On the Theory of Scales of Measurement, *Science*, New Series, Vol. 103, No. 2684. (Jun. 7, 1946), pp. 677-680. Available at: [http://marces.org/EDMS623/Stevens%20SS%20\(1946\)%20On%20the%20Theory%20of%20Scales%20of%20Measurement.pdf](http://marces.org/EDMS623/Stevens%20SS%20(1946)%20On%20the%20Theory%20of%20Scales%20of%20Measurement.pdf)
41. Tomaschek, K., Olechowski, A. L., Eppinger, S. D., & Joglekar, N. R. (2016). A Survey of Technology Readiness Level Users. In INCOSE International Symposium (IS 2016) (Vol. 26, pp. 2101–2117). Edinburgh, UK. <https://doi.org/10.1002/j.2334-5837.2016.00283.x>
42. US Department of Defense, “Technology Readiness Assessment (TRA) Guidance,” 2011. Available: <http://www.acq.osd.mil/chieftechologist/publications/docs/TRA2011.pdf>.
43. Yasseri S. (2013). “Subsea system readiness level assessment” *Int. Journal of Underwater Technology* 31: 77–92
44. Yasseri S., (2014). “Application of system engineering to subsea development,” *Int. Journal of Underwater Technology*, 32:93–109
45. Yasseri S. (2015). Interface management of subsea field development. *Underwater Technology* Vol.33, No. 1, pp 41–57.
46. Yasseri S. (2015). “Evidence-based subsea engineering,” *Int. Journal of Underwater Technology* Vol. 32, No. 4, pp. 231-244.
47. Yasseri S., (2016), “A measure of subsea readiness level development,” *Int. Journal of Underwater Technology* Vol. 33, No. 4, pp 215-228.
48. Yasseri S. Bahai, H and Yasseri, R., (2018a). “A Systems Engineering Framework for Delivering Reliable Subsea Equipment,” 2018-TPC-035, ISOPE 2018, Japan. Accepted for publication
49. Yasseri S. Bahai, H and Yasseri, R., (2018b). “Reliability Assurance of Subsea Production Systems: A Systems Engineering Framework, *IJCOE* Vol.1, No. 1, pp 31-46.