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Enhancing Technology Readiness Assessment: The Engineering Severity Level Methodology and the Technical Readiness Level+ Classification

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ABSTRACT In this article, the author proposes a novel methodology to overcome the outstanding challenges in accurately assessing technology readiness for final real-world applications. The engineering severity level is a conceptual methodology that provides a simple, standardized, and quantitative method for assessing technology suitability in relation to real-world environments. It is a standalone assessment concept that offers advantages in generating an evidence base for accurate technology readiness assessment and early identification of developmental roadblocks derived from real-world requirements. Moreover, the methodology can be applied as a universal basis to enhance the technical readiness level classification assessment criteria. The benefits are exemplified in assessing quantum technologies for position, navigation, and timing requirements in defense applications.

INDEX TERMS Prototype development, quantum technology, systems engineering, technology assessment, technology development, technology maturity level, technology readiness, technology readiness level (TRL).

I. INTRODUCTION

The development of new technology is of paramount importance for industrial sectors, government bodies, and financial investors in maintaining commercial leadership and national capabilities. However, identifying specific areas for investment can be challenging, and these decisions can significantly impact investors' confidence in novel technologies and the ultimate viability of products.

To make informed decisions, technology developers and investors require an accurate assessment of technology's readiness in terms of both performance and physical form factor relative to its intended real-world application. For novel technologies that are in the early stages of development, understanding their technical readiness is crucial. This entails evaluating their potential performance, capabilities, and areas for further refinement and optimization.

On the other hand, for technologies that have undergone significant real-world testing and achieved a certain level of market acceptance, understanding their technological maturity becomes more important. This involves assessing factors such as stability, reliability, and market acceptance to determine if the technology is ready for widespread implementation.

Assessing technology's readiness has been a persistent challenge and an active area of research since the 1950s.

The technology readiness level (TRL) classification system [1] has gained widespread adoption.[1] However, the TRL system has faced criticism for its criteria subjectivity, resulting in program delivery shortcomings [2], [3], [4], [5], [6], [7]. This subjectivity is particularly evident in the transition from TRL 4 to 8, commonly referred to as the "Valley of Death," where innovations often struggle to progress successfully. These persistent challenges highlight the need for a readiness

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[1] This extensive use includes the U.K. Ministry of Defence (MoD) (2001), North Atlantic Treaty Organization (NATO) (2008), Boeing, the European Space Agency (2008), U.S. Homeland Security (2009), U.S. Department of Defense (DoD) (2001), the International Organization for Standardization (2013), Google, Raytheon, John Deere, and BP (2015), and the EU Horizon programme (2020).

methodology that provides clear evidence for classifying technology readiness.

This article presents the engineering severity level (ESL), a novel technology readiness assessment methodology. The methodology provides a standalone, evidence-based assessment capability for determining a technology's suitability and readiness for a given real-world application. In addition, the TRL+ classification is presented, where evidence derived from the ESL methodology provides a robust framework to enhance the current TRL classification assessment criteria.

The article serves as a comprehensive guide for technology developers in government, academia, and industrial sectors, advocating its adoption as a reliable methodology for evaluating technology development relative to the intended environment.

II. BACKGROUND

The TRL classification system is a widely adopted method for assessing technology readiness and promoting testing and verification. However, it has received criticism that can be can be summarized into the following four dominant contributing factors.

1) The TRL classification system focuses on technology readiness but overlooks functional aspects within a system and real-world operational outcomes. It also treats technology as a standalone entity, disregarding its holistic capabilities [11], [12], [13], [14].
2) TRL classification is subjective, with varying interpretations of the world and acceptance of risks. Notably, there is no standardized measure of the operational physical environment between TRL 5 and 7 [15], [16], [17].
3) Technology readiness does not reflect maturity timelines or capture development lifecycles needed for progression. The scale is a rigid binary metric, lacking functionality to accommodate evolving expectations over time. [11], [17], [18], [19], [20], [21], [22], [23], [24].
4) TRL classification identifies potential risk areas but lacks a metric to assess associated risks or the difficulty of transitioning between readiness levels [4], [6], [15].

Attempts have been made to overcome these challenges; with the creation of supporting software and calculators [7], [8], a classification framework [9], and a readiness assessment guide [10], challenges persist.

The subjectivity and limited functionality of the TRL have been identified as an attributing factor to failed technology insertion [2], [25], [26], [27], [28], [29], and this is accentuated by overconfidence bias [26], [27], [28], [29], [30], [31] in the ability to deliver technology.

Numerous alternative methods have been proposed to overcome these challenges, with one review identifying 409 relevant papers on the subject [24]. These models, methods, and classifications range from simple adaptations to the current TRL metric [32], [33] or linking TRL to other standardized architecture frameworks [22] to a plethora of readiness levels that incorporate TRL, each offering an improved ability to accurately assess technology readiness or maturity. A nonexhaustive summary of relevant readiness levels and how they interconnect is presented in Fig. 1.

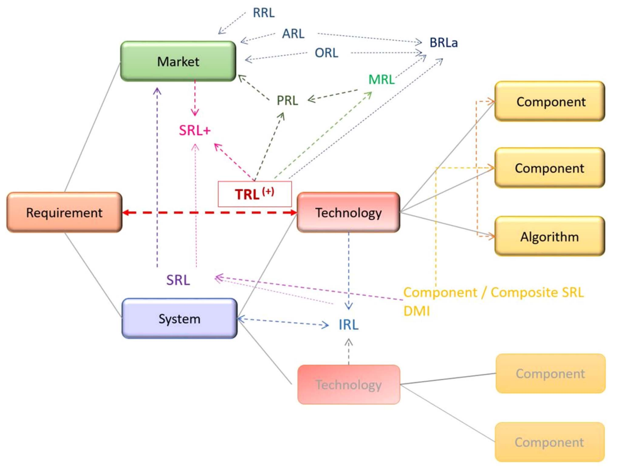
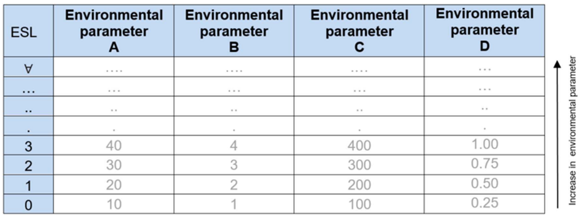


FIGURE 1. Summary of readiness level classification approaches and how they interlink in support of the development of technology and assessing readiness/maturity. Those included are the TRL [1], the system readiness level (SRL) including the component and composite SRL [13], the development maturity index (DMI) [15], the integration readiness level (IRL) [37], the system readiness level plus (SRL+) [38], the balance readiness level (BRLa) [39], which includes regulatory readiness level (RRL), the acceptance readiness level (ARL), the organization readiness level (ORL), and manufacturing readiness level (MRL) [40], [41].

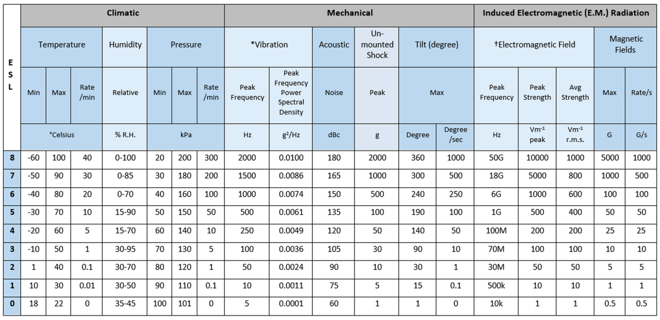
The matrices, indices, and assessments presented in Fig. 1 vary in complexity and often require a subject matter expert (SME) to interpret and assess the technology's readiness and maturity with the final operational requirement. One such example is the Cornford and Sarsfield developmental maturity index (DMI) [15], which was created as a replacement for TRL and uses subjective measurements to link the system-of-systems approach. The DMI repeatedly assesses technology key engineering performance parameters throughout the development cycle, addressing the issue of technology maturity assessment by including developmental targets. However, each component's targets are unique and require an SME to assign and negotiate the acceptance development cycle. A significant advancement in technology development assessment is the ability to quantify technology's readiness in terms of readiness of the internal system integration between components, provided by Sauser's system readiness level (SRL) [13]. Since the creation of the SRL, further developments have been made linking technology development assessment with system-of-systems and systems engineering architectures [34], [35], [36].

Improved computer modeling and "digital twins" can provide quantifiable evidence of technology readiness, but their cost increases with the reliability and complexity of the models. As a result, their use in technology development can be limited. Therefore, there is a need for a standardized, simplistic tool in industry and academia to objectively define technology readiness and quantify its overall capability against real-world operational requirements.



ESL	Environmental parameter A	Environmental parameter B	Environmental parameter C	Environmental parameter D
∀	....	....	....	...
...	...	...	...	...
..	..	..	..	..
.	.	.	.	.
3	40	4	400	1.00
2	30	3	300	0.75
1	20	2	200	0.50
0	10	1	100	0.25

FIGURE 2. **ESL matrix example.**



ESL	Climatic							Mechanical						Induced Electromagnetic (E.M.) Radiation				
	Temperature			Humidity	Pressure			*Vibration		Acoustic	Un-mounted Shock	Tilt (degree)		†Electromagnetic Field			Magnetic Fields	
	Min	Max	Rate /min	Relative	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Max	Rate/s
	°Celsius			% R.H.	kPa			Hz	g^2/Hz	dBc	g	Degree	Degree /sec	Hz	Vm^{-1} peak	Vm^{-1} r.m.s.	G	G/s
8	-60	100	40	0-100	20	200	300	2000	0.0100	180	2000	360	1000	50G	10000	1000	5000	1000
7	-50	90	30	0-85	30	180	200	1500	0.0086	165	1000	300	500	18G	5000	800	1000	500
6	-40	80	20	0-70	40	160	100	1000	0.0074	150	500	240	250	6G	1000	600	100	100
5	-30	70	10	15-90	50	150	50	500	0.0061	135	100	190	100	1G	500	400	50	50
4	-20	60	5	15-70	60	140	10	250	0.0049	120	50	140	50	100M	200	200	25	25
3	-10	50	1	30-95	70	130	5	100	0.0036	105	30	90	10	70M	100	100	10	10
2	1	40	0.1	30-70	80	120	1	50	0.0024	90	10	30	1	30M	50	50	5	5
1	10	30	0.01	30-50	90	110	0.1	10	0.0011	75	5	15	0.1	500k	10	10	1	1
0	18	22	0	35-45	100	101	0	5	0.0001	60	1	1	0	10k	1	1	0.5	0.5

* Vibration: Peak acceleration power spectral density ESL value at the frequency ESL value stated.
† Electromagnetic (E.M.) Radiation: Peak and average field strengths at the EM peak frequency ESL value.

FIGURE 3. **Example of real-world ESL matrix, populated with representative values for a range of sea, land, and air military platforms.**

This article investigates the creation of a methodology called the ESL, which consists of two data capture tools: the ESL matrix and the size, weight, and power (SWaP) matrix. The ESL methodology aims to assess technology development readiness based on final operational requirements, providing an evidence base for readiness classification.

In the following sections, a detailed description of the ESL matrix and the SWaP matrix tools are provided, outlining their functions and how they contribute to the overall ESL methodology. In addition, this article will explore how these tools can complement and enhance the TRL classification assessment criteria. Furthermore, an example will be presented in Section II-E, demonstrating the application of these tools in the emerging field of quantum technology and their relevance to demanding defense and security platforms.

A. METHODOLOGY

The ESL methodology is a comprehensive approach to assessing technology development readiness and platform compatibility. It consists of the ESL matrix, SWaP matrix, and the mapping associated parameters (MAP) process.

The ESL matrix evaluates technology's performance and functionality based on environmental parameters and operational requirements. It defines parameters and their acceptable ranges (see Section II-B) and determines platform technology requirements (see Section II-C). It also assesses technology capability to withstand different environmental conditions (see Section II-D).

The MAP process correlates data from the ESL matrix and technology capability matrix to evaluate compatibility with the platform. It provides insights for targeted research and investment to enhance technology readiness (see Section II-E).

The SWaP matrix analyzes the size, weight, and power characteristics of the technology relative to the platform. It quantitatively assesses physical attributes and feasibility through the MAP process (see Section II-F).

The "TRL+" classification enhances the TRL by employing the ESL methodology. It offers a comprehensive and objective evaluation of technology readiness by considering environmental, physical, and technical aspects (see Section II-G).

B. ESL DATASET MATRIX

A technology or system must operate within a technical performance envelope in a platform operating in a real-world environment. The ESL matrix (see Fig. 2) captures the range of platform environments by bringing together disparate data sources and common platform environment parameters in a single dataset. The severity of each parameter is indicated along the matrix column's vertical axis, ranging from a benign laboratory environment (ESL = 0) to the most extreme platform environments that technology must withstand (ESL = ∀).

The ESL matrix tool is designed to represent any environmental parameter, with user-definable ranges and increments to capture the necessary granularity of operational environments.

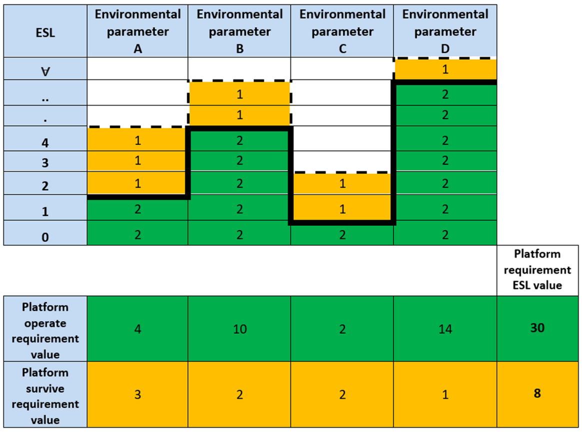
An investigation was conducted to evaluate military platform environmental parameters and it was found that physical conditions, such as temperature, pressure, acoustic noise, vibration, and electromagnetic field characteristics, are common across all platforms. The investigation also found that environmental parameter severity varies by platform type, with large ships having relatively benign conditions compared to tanks or rockets. In a real-world scenario, a technology must operate in a complex combination of environmental events over timescales relating to platform operation and service lifetime. The values within the ESL matrix represent an approximate single independent event at a specific location within a platform but can be applied to real-world scenarios as a snapshot of common platform environmental parameters.

From the investigation, an ESL matrix (see Fig. 3) was created ten military platforms with different internal operational environments that technology is required to perform within. The ten military platforms represented a variety of platforms from the land and sea domains.

C. PLATFORM REQUIREMENTS ESL MATRIX

The purpose of technology is to provide continuous performance or survive extreme environmental events, resuming operation when conditions return to normal.

The ESL platform matrix serves to differentiate between parameters that are essential for technological operation and those that are necessary for survival. This distinction is visually represented by color-coded cells, with green indicating operational parameters and yellow indicating survivable parameters. To quantify their relative significance, each color is



ESL	Environmental parameter A	Environmental parameter B	Environmental parameter C	Environmental parameter D	
∀				1	
..		1		2	
.		1		2	
4	1	2		2	
3	1	2		2	
2	1	2	1	2	
1	2	2	1	2	
0	2	2	2	2	
					Platform requirement ESL value
Platform operate requirement value	4	10	2	14	30
Platform survive requirement value	3	2	2	1	8

FIGURE 4. Platform ESL requirement matrix with platform profiles and profile values, which are used in the MAP process in Section II-D. Here, green denotes operate with a technical performance and yellow survive. The solid and broken lines in bold are the platform's operation and survival profiles, respectively.

assigned a weighted score in relevance to the importance of the function, which subsequently contributes to a comparative best-fit quantitative analysis when combined with technology capability. This analysis yields a "technology suitability percentage" value. In the example depicted in Fig. 4, the weighted value assigned to the operation function is greater (two) than that of the survival requirement function (one).

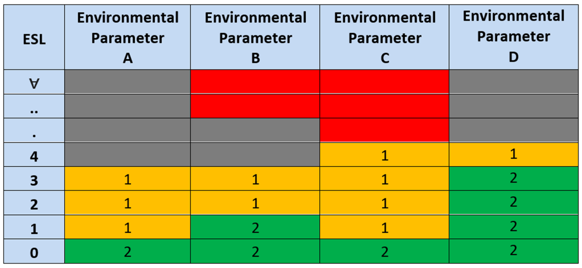
The platform operation value is determined by summing the values below the solid black line, while the platform survival value is determined by summing the values below the broken black line but above the solid black line. In the specific example presented in Fig. 4, these values amount to 30 and 8, respectively. These calculated values play a crucial role in the MAP-ESL process, which is described in detail in Section II-E of this article.

D. TECHNOLOGY CAPABILITY ESL MATRIX

The same ESL matrix is used to capture a technology's capability to function in diverse environments, employing the same methodology as the platform requirement matrix.

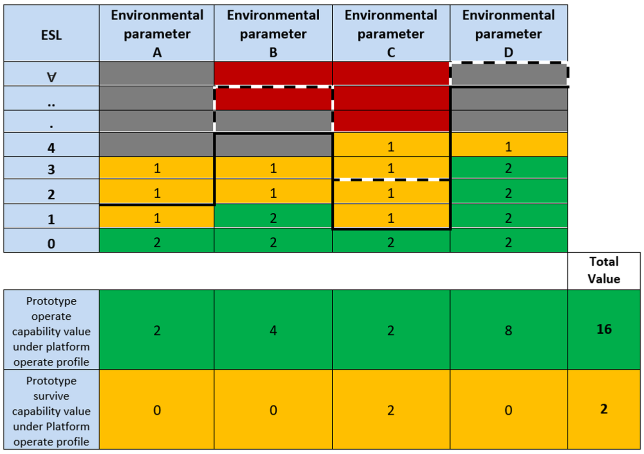
The ESL matrix identifies the technology's operational aspects (green) associated with optimal technical performance set by the ESL tool user and its survivability aspects (yellow) linked to degraded or no technical performance capabilities. Numerical values are allocated to each aspect based on the weighting employed within the platform requirement ESL matrix.

Furthermore, the ESL matrix can capture additional information, such as conditions where the technology is unproven (gray) or fundamentally unable to survive (red). However, this information does not receive a weighted score. Fig. 5 illustrates the technology capability ESL matrix, featuring the numerical values employed in the MAP process described in Section II-E.



ESL	Environmental Parameter A	Environmental Parameter B	Environmental Parameter C	Environmental Parameter D
∀	⬛	🟥	🟥	⬛
..	⬛	🟥	🟥	⬛
.	⬛	⬛	🟥	⬛
4	⬛	⬛	1	1
3	1	1	1	2
2	1	1	1	2
1	1	2	1	2
0	2	2	2	2

FIGURE 5. Technology capability ESL Matrix. Numerical values are used in the MAP process described in Section II-D. Here, red indicates the technology is unable to operate, and gray represents that the performance is unknown.



ESL	Environmental parameter A	Environmental parameter B	Environmental parameter C	Environmental parameter D	
∀	⬛	🟥	🟥	⬛	
..	⬛	🟥	🟥	⬛	
.	⬛	⬛	🟥	⬛	
4	⬛	⬛	1	1	
3	1	1	1	2	
2	1	1	1	2	
1	1	2	1	2	
0	2	2	2	2	
					Total Value
Prototype operate capability value under platform operate profile	2	4	2	8	16
Prototype survive capability value under Platform operate profile	0	0	2	0	2

FIGURE 6. ESL-MAP analysis: A technology environmental capability ESL matrix with platform requirement profiles mapped (solid and dashed lines) and MAP assessment values.

E. MAPPING ASSOCIATED PARAMETERS (MAP)

The MAP numerical analysis provides a visual identification method that highlights capability gaps, discrepancies, or mismatches between a technology capability and platform requirements. This identification enables targeted technological development or tradeoffs between nonkey performance requirements, critical parameters, and resource allocation. The analysis also derives a coarse percentage fit of the technology's environmental functional capability for the platform in question, with details indicating opportunities for compromise and development.

The MAP-ESL matrix (see Fig. 6) is created by overlaying the platform requirement profiles created in Fig. 4 onto the technology capability ESL matrix).

To ensure the integrity of the MAP-ESL process and minimize bias, both the platform technology requirements matrix and the technology capability ESL matrix must be identical. Maintaining consistency between these matrices reduces potential biases that may arise from divergent interpretations or subjective assessments. By aligning the matrices closely, a standardized framework is established, accurately representing the environmental conditions in which the technology functions. This approach ensures a fair and unbiased evaluation of the technology's performance and its ability to withstand real-world platform environments.

The overall percentage fit of the technology capability to platform requirements is deduced by determining both the suitability percentages for the technology to meet the platform's operation requirements and platform's survival requirements.

The suitability percentage of the technology to meet the platform's operation requirement is evaluated by summing the total number of green cell values under the platform operation profile (solid black line) and comparing the value with the platform operation profile value (see Fig. 4). In the example in Fig. 6, the total green cell value is 16, and the platform operation profile value is 30. Therefore, the percentage fit of the technology's operation capability to the platform's operation requirement is calculated as (16/30) × 100 = 53

Similarly, the suitability percentage of the technology to meet the platform's survival requirement is evaluated by comparing the sum of total values in each yellow cell that lies between the platform survival and operation profiles with the platform survival profile value of eight (see Fig. 6). Hence, the percentage fit of the technology's survival capability to the platform's survival requirement is (2/8) × 100 = 25

Caution should be exercised when assessing the technology's suitability to meet the platform's environmental survival requirements, as the technology's capability may exceed the platform's needs. In such cases, areas of excessive capability are adjusted by downgrading the technology's functionality from operate to survive within the platform's environmental survival functionality requirement profile.

The overall suitability of the technology to meet the platform's environmental requirements is determined by combining the percentage fits of its operation and survival capabilities. In this example, the overall suitability percentage is the average of the technology's operation and survival percentage fits, which are 53% and 25%, respectively. This is calculated as (53% + 25%) / 2 = 39%.

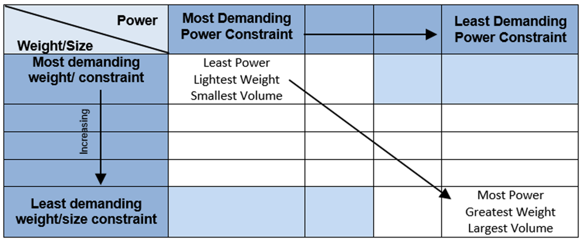
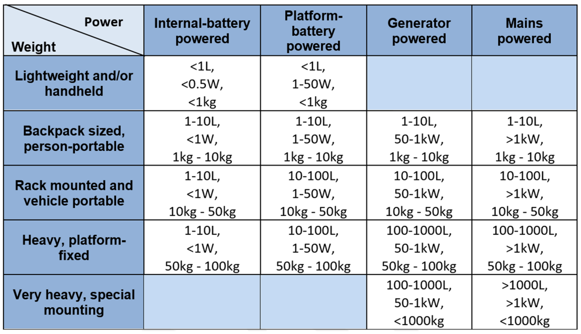
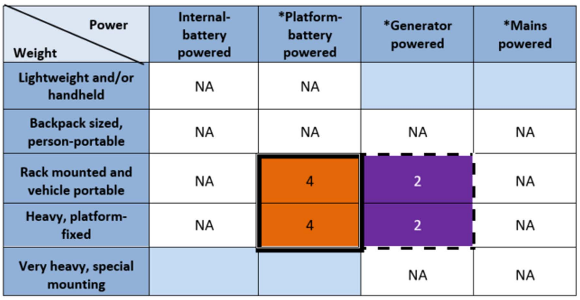


FIGURE 7. Example of a SWaP matrix.



Power / Weight	Internal-battery powered	Platform-battery powered	Generator powered	Mains powered
Lightweight and/or handheld	<1L, <0.5W, <1kg	<1L, 1-50W, <1kg		
Backpack sized, person-portable	1-10L, <1W, 1kg - 10kg	1-10L, 1-50W, 1kg - 10kg	1-10L, 50-1kW, 1kg - 10kg	1-10L, >1kW, 1kg - 10kg
Rack mounted and vehicle portable	1-10L, <1W, 10kg - 50kg	10-100L, 1-50W, 10kg - 50kg	10-100L, 50-1kW, 10kg - 50kg	10-100L, >1kW, 10kg - 50kg
Heavy, platform-fixed	1-10L, <1W, 50kg - 100kg	10-100L, 1-50W, 50kg - 100kg	100-1000L, 50-1kW, 50kg - 100kg	100-1000L, >1kW, 50kg - 100kg
Very heavy, special mounting			100-1000L, 50-1kW, <1000kg	>1000L, >1kW, <1000kg

FIGURE 8. Real-world SWaP matrix.



Power / Weight	Internal-battery powered	*Platform-battery powered	*Generator powered	*Mains powered
Lightweight and/or handheld	NA	NA		
Backpack sized, person-portable	NA	NA	NA	NA
Rack mounted and vehicle portable	NA	4	2	NA
Heavy, platform-fixed	NA	4	2	NA
Very heavy, special mounting			NA	NA

FIGURE 9. Platform SWaP requirement matrix, with platform profiles where orange indicates the current requirement and purple indicates the potential requirement (meaning the platform would require modification). The solid and dashed outlined boxes represent the current and potential SWaP requirements.

F. SWAP AND MAP PROCESS

Platform SWaP constraints are crucial in determining a technology's ability to fulfil a functional role on a platform.

The ESL methodology employs the use of the SWaP matrix, a tool that captures the three variable attributes of technology intended for platform integration in a single 2-D dataset, as shown in Fig. 7. Each cell represents a SWaP with the most severe constraints located in the top left matrix cell and the least severe in the bottom right matrix cell. However, the value of each cell can be customized to meet the user's requirements.

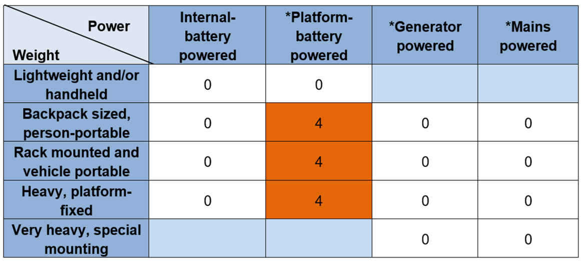
From the military platform investigation, a SWaP matrix was created to represent the SWaP constraints of the ten identified platforms. This is shown in Fig. 8.

To assess the suitability of a technology to a platform requirement, the MAP-SWaP process is applied.

Each SWaP matrix cell is color-coded and assigned a weighted score to represent the current state (orange, with a value of four in the example shown in Fig. 9) or potential state (purple, with a value of two) of the platform's SWaP requirements. Here, the term "potential" refers to the ability to modify a platform to accommodate a larger technology SWaP. A solid black line is drawn around the perimeter of the cells that correspond to the current SWaP requirement, while a dashed black line is drawn around the perimeter of the cells that corresponds to the potential platform SWaP requirement.

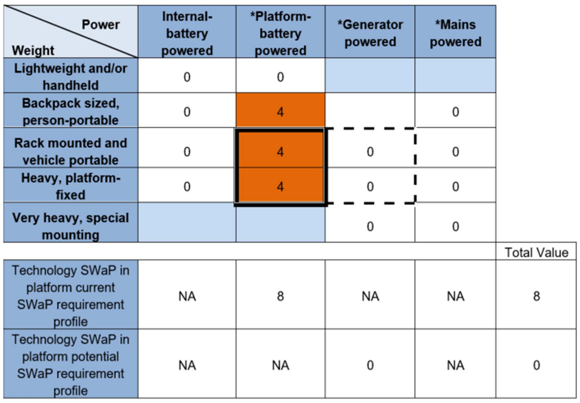
An example of a technology's current SWaP is presented in Fig. 10, where each SWaP attribute is assigned a numerical value identical to those used within the platform SWaP requirement matrix, allowing for a direct comparison.

To evaluate the technology's suitability to meet the platform's SWaP requirements, the platform SWaP attribute profiles are overlayed onto the technology SWaP capability matrix, as presented in Fig. 11.



Weight \ Power	Internal-battery powered	*Platform-battery powered	*Generator powered	*Mains powered
Lightweight and/or handheld	0	0		
Backpack sized, person-portable	0	4	0	0
Rack mounted and vehicle portable	0	4	0	0
Heavy, platform-fixed	0	4	0	0
Very heavy, special mounting			0	0

FIGURE 10. Technology SWaP capability matrix.



Weight \ Power	Internal-battery powered	*Platform-battery powered	*Generator powered	*Mains powered	
Lightweight and/or handheld	0	0			
Backpack sized, person-portable	0	4		0	
Rack mounted and vehicle portable	0	4	0	0	
Heavy, platform-fixed	0	4	0	0	
Very heavy, special mounting			0	0	
					Total Value
Technology SWaP in platform current SWaP requirement profile	NA	8	NA	NA	8
Technology SWaP in platform potential SWaP requirement profile	NA	NA	0	NA	0

FIGURE 11. Results of the MAP-SWaP process, where the platform SWaP requirement profiles (solid and dashed) have been overlaid onto the technology SWaP capability matrix.

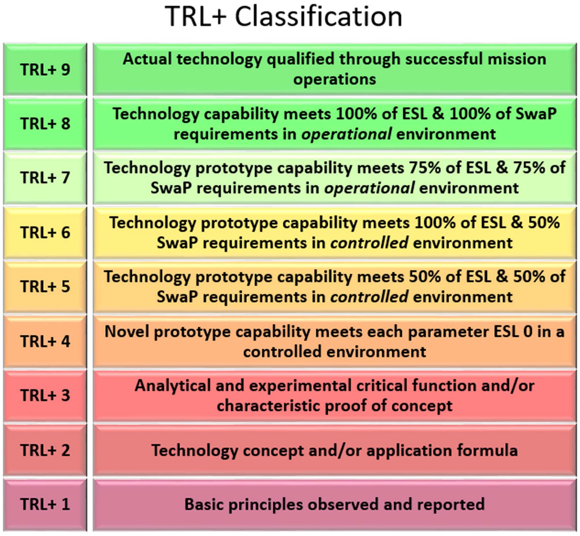
In the example presented in Fig. 11, the technology meets 100% of the current platform SWaP requirement but 0% of the potential requirement. Overall, the MAP-SWaP process provides a systematic approach to evaluating a technology's SWaP capabilities to meet the platform's SWaP requirements. It allows for the identification of areas where the technology's SWaP capability exceeds or falls short of the platform's SWaP requirements, thereby providing opportunities for development or compromise.

G. TRL REDEFINED

The ESL analysis method provides an accessible method for targeting areas of interest to technology integrators, developers, and investors. In addition, it offers an auditable evidence trail for technology development and acquisition, while simultaneously highlighting contextual technology limits in real-world applications. The ESL readiness assessment serves as a standalone methodology, but it can provide standardized quantitative assessment criteria within the TRL classification and provide evidence-based definitions, as shown in Fig. 12.

The TRL+ESL (or simply TRL+) classification is based on the MoD TRL classification [42], but it incorporates the evidence derived from the ESL and SWaP matrices to redefine the definitions of levels 4–8.

In the TRL definition, TRL 4 represents the basic validation of a technology in a laboratory environment without SWaP constraints, which equates to ESL 0 across all environmental parameters within the ESL matrix. Hence, a novel technology is TRL+ 4 when demonstrating a set performance capability within a benign laboratory environment with environmental parameters defined by ESL 0.



TRL+ Classification

TRL+ 9	Actual technology qualified through successful mission operations
TRL+ 8	Technology capability meets 100% of ESL & 100% of SwaP requirements in *operational* environment
TRL+ 7	Technology prototype capability meets 75% of ESL & 75% of SwaP requirements in *operational* environment
TRL+ 6	Technology prototype capability meets 100% of ESL & 50% SwaP requirements in *controlled* environment
TRL+ 5	Technology prototype capability meets 50% of ESL & 50% of SwaP requirements in *controlled* environment
TRL+ 4	Novel prototype capability meets each parameter ESL 0 in a controlled environment
TRL+ 3	Analytical and experimental critical function and/or characteristic proof of concept
TRL+ 2	Technology concept and/or application formula
TRL+ 1	Basic principles observed and reported

FIGURE 12. Example of TRL classification descriptions redefined using the ESL/SWaP matrices tools and MAP process methodology.

Currently, the environment and SWaP of TRL 5, 6, 7, and 8 are not quantitatively defined. However, applying the ESL and SWaP matrices can lead to quantitative and standardized metrics of SWaP within the TRL classification definition as follows.

1) *TRL+ 5:* When demonstrating a set performance capability within a controlled environment that meets a minimum of 50% of an ESL platform environment requirement and a form factor and power capability matching at least 50% of the SWaP requirement.
2) *TRL+ 6:* When demonstrating a set performance capability within a controlled environment that meets a minimum of 100% of an ESL platform environment requirement and with a form factor and power capability meeting at least 50% of the SWaP requirement.
3) *TRL+ 7:* When demonstrating a set performance capability within the intended operational environment that meets a minimum of 75% of an ESL platform environment requirement with a form factor and power capability meeting at least 75% of the SWaP requirement.
4) *TRL+ 8:* When demonstrating a set performance capability within the intended operational environment that meets 100% of an ESL platform environment requirement with a form factor and power capability meeting at least 75% of the SWaP requirement.

The ESL architect sets the definition of a controlled environment, which can include laboratory simulated testing, testing a prototype on a platform that is not the intended final platform, and/or on the intended platform when not carrying out full operational maneuvers.

The ESL readiness assessment methodology is not intended to be used as a standalone systems engineering process but as a standardized methodology for quantitatively assessing and defining technology capability relative to its final application. However, applying the ESL methodology to redefine the definitions within the TRL classification allows the TRL+ to be used alongside many of the systems engineering tools and classifications mentioned in Fig. 1.

It must be noted that the percentage values assigned to each TRL classification could result in subjectivity if different users assign different percentage values. Therefore, to ensure consistency and comparability, it is suggested that the scheme proposed here creates a standardized TRL+ classification. This would establish a common framework where the assigned percentage values for prototype capabilities, ESL, and SWaP are standardized, thereby eliminating potential discrepancies arising from subjective interpretations.

H. REDUCING SUBJECTIVITY

Technology's readiness assessments are complex tasks influenced by subjectivity and human psychology. Subjectivity can lead to rushed decisions due to discomfort with indecision [43]. To mitigate biases, methodologies like the ESL promote a deliberate and evidence-based approach, thoroughly examining technology performance and form factor, providing additional information to the user for decision making.

When using ordinal scales like the TRL classification, subjectivity can come into play if it is used outside of its intended application. TRL categorizes technologies into levels ranging from 1 to 9, but the intervals between levels are not precisely quantifiable. Arithmetic operations are not applicable to ordinal scales as they represent relative ranking, not precise measurements.

The ESL methodology can be considered an ordinal scale as it provides information on environmental severity levels but not the effort required to transition between them. This context-specific information is typically provided by technology developers or considered separately and subject to subjectivity. However, the ESL methodology provides quantitative information on the next level, prompting discussions on the effort required to reach the next severity level.

Recognizing the influence of human psychology and the limitations of the ESL methodology is crucial when conducting technology readiness assessments. The ESL methodology serves as a structured framework, guiding decision makers to conduct comprehensive evaluations considering factors like technology performance, form factor, and manufacturing capabilities.

III. INVESTIGATION

Quantum technology [44] has vast potential applications with a significant impact on humanity, similar to the transistor. However, the underlying science is complex, and developing low TRL quantum technology is expensive and requires targeted investment. Without evidence-based development, the resulting technology may not be fit for purpose.

The U.K. defense and security sector requires highly accurate and resilient position, navigation, and timing (PNT). When global navigation satellite systems are unavailable, an inertial navigation system (INS) error accumulates, compromising mission success. The Defence Science and Technology Laboratory's (Dstl) Quantum Sensing Project aims to augment the current INS with next-generation quantum sensing capability of achieving a robust and enduring PNT solution. This section explains how the ESL methodology was trialed during a quantum-augmented PNT (Q-PNT) funding call from the Defence and Security Accelerator (DASA), a Ministry of Defence innovation funding body.

A. Q-PNT FIRST ADOPTERS

For the investigation, ten first-adopter platforms were identified for an investigation into quantum-augmented position, navigation, and timing (Q-PNT). These platforms represent various domains and operational complexities, with corresponding environmental requirements captured in ESL matrices. The platforms cannot be identified due to their classified nature, but two platforms, A and B, were chosen for proof of concept demonstration, as shown in Figs. 13 and 14. For both platforms, the "operate" attribute requires technology to meet set performance 90% of the time, and the "survive" attribute requires it to operate immediately within the "operate" environmental parameter range.

B. Q-PNT INVESTIGATION

The quantum sensing DASA research call "Reducing Reliance on Global Navigation Satellite Systems with Q-PNT," was released on 2nd November 2020. The call aimed to reduce reliance on global navigation satellite systems by focusing on sensing technology between TRL 4 to 6, such as atomic clocks, quantum-enabled accelerometers, gyroscopes, gravity, and magnetic field sensors. Research proposals were required to provide evidence of advanced sensing performance or enhanced environmental operational capability within a five-year time frame through six-month feasibility studies. Suppliers were required to use the ESL and SWaP matrices to show the potential progression of the device's physics[2] package and driving devices from the current technical prototype to the future operational environmental capability.

Suppliers were requested to utilize the ESL matrix (see Fig. 3) with color coding (see Fig. 15) and the SWaP matrix (see Fig. 8) with color coding (see Fig. 16) to demonstrate the progression of the device's physics package and driving devices. They were also invited to comment on each technology's ESL matrices regarding technical performance capabilities for environmental conditions. An example of a proposed technology's current and future environmental and SWaP capability is presented in Fig. 17(a)–(c), respectively. Supplier comments have been removed to maintain confidentiality.

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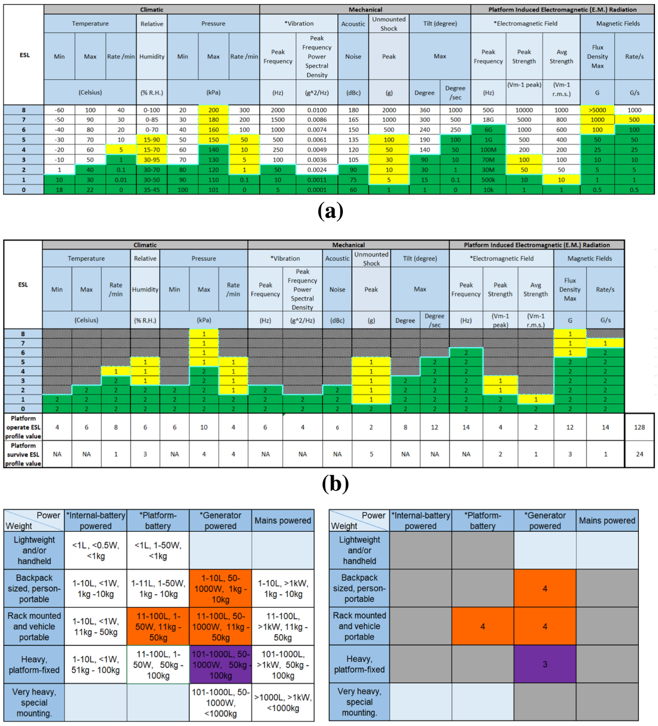
[2] Physics package and driving devices include all system components other than power generation, such as lasers, optics, acoustic, optical modulators, amplifiers, etc.



ESL	Climatic							Mechanical						Platform Induced Electromagnetic (E.M.) Radiation				
	Temperature			Relative	Pressure			*Vibration		Acoustic	Unmounted Shock	Tilt (degree)		*Electromagnetic Field			Magnetic Fields	
	Min	Max	Rate /min	Humidity	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Flux Density Max	Rate/s
	(Celsius)			(% R.H.)	(kPa)			(Hz)	(g^2/Hz)	(dBc)	(g)	Degree	Degree /sec	(Hz)	(Vm-1 peak)	(Vm-1 r.m.s.)	G	G/s
8	-60	100	40	0-100	20	200	300	2000	0.0100	180	2000	360	1000	50G	10000	1000	>5000	1000
7	-50	90	30	0-85	30	180	200	1500	0.0086	165	1000	300	500	18G	5000	800	1000	500
6	-40	80	20	0-70	40	160	100	1000	0.0074	150	500	240	250	6G	1000	600	100	100
5	-30	70	10	15-90	50	150	50	500	0.0061	135	100	190	100	1G	500	400	50	50
4	-20	60	5	15-70	60	140	10	250	0.0049	120	50	140	50	100M	200	200	25	25
3	-10	50	1	30-95	70	130	5	100	0.0036	105	30	90	10	70M	100	100	10	10
2	1	40	0.1	30-70	80	120	1	50	0.0024	90	10	30	1	30M	50	50	5	5
1	10	30	0.01	30-50	90	110	0.1	10	0.0011	75	5	15	0.1	500k	10	10	1	1
0	18	22	0	35-45	100	101	0	5	0.0001	60	1	1	0	10k	1	1	0.5	0.5

(a)

ESL	Climatic							Mechanical						Platform Induced Electromagnetic (E.M.) Radiation					
	Temperature			Relative	Pressure			*Vibration		Acoustic	Unmounted Shock	Tilt (degree)		*Electromagnetic Field			Magnetic Fields		
	Min	Max	Rate /min	Humidity	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Flux Density Max	Rate/s	
	(Celsius)			(% R.H.)	(kPa)			(Hz)	(g^2/Hz)	(dBc)	(g)	Degree	Degree /sec	(Hz)	(Vm-1 peak)	(Vm-1 r.m.s.)	G	G/s	
8						1											1		
7						1											1	1	
6						1								2			1	2	
5				1		1	1				1		2	2			2	2	
4			1	1		2	1				1		2	2			2	2	
3			2	1		2	1				1	2	2	2	1		2	2	
2		2	2	2	2	2	1	2		2	1	2	2	2	1		2	2	
1	2	2	2	2	2	2	2	2	2	2	1	2	2	2	2	1	2	2	
0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
Platform operate ESL profile value	4	6	8	6	6	10	4	6	4	6	2	8	12	14	4	2	12	14	128
Platform survive ESL profile value	NA	NA	1	3	NA	4	4	NA	NA	NA	5	NA	NA	NA	2	1	3	1	24

(b)

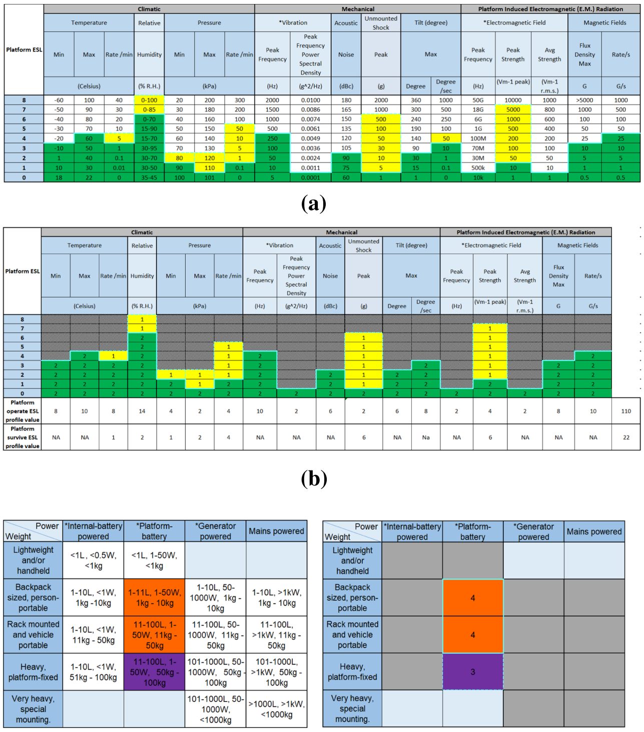
Power Weight	*Internal-battery powered	*Platform-battery	*Generator powered	Mains powered
Lightweight and/or handheld	<1L, <0.5W, <1kg	<1L, 1-50W, <1kg		
Backpack sized, person-portable	1-10L, <1W, 1kg -10kg	1-11L, 1-50W, 1kg - 10kg	1-10L, 50-1000W, 1kg - 10kg	1-10L, >1kW, 1kg - 10kg
Rack mounted and vehicle portable	1-10L, <1W, 11kg - 50kg	11-100L, 1-50W, 11kg - 50kg	11-100L, 50-1000W, 11kg - 50kg	11-100L, >1kW, 11kg - 50kg
Heavy, platform-fixed	1-10L, <1W, 51kg - 100kg	11-100L, 1-50W, 50kg - 100kg	101-1000L, 50-1000W, 50kg - 100kg	101-1000L, >1kW, 50kg - 100kg
Very heavy, special mounting.			101-1000L, 50-1000W, <1000kg	>1000L, >1kW, <1000kg

(c)

Power Weight	*Internal-battery powered	*Platform-battery	*Generator powered	Mains powered
Lightweight and/or handheld				
Backpack sized, person-portable			4	
Rack mounted and vehicle portable		4	4	
Heavy, platform-fixed			3	
Very heavy, special mounting.				

(d)

FIGURE 13. Platform A. (a) Platform ESL matrix. (b) ESL matrix with platform profiles (blue solid and dashed line) and profile values. (c) Platform SWaP matrix. (d) SWaP matrix profiles.



Platform ESL	Climatic							Mechanical						Platform Induced Electromagnetic (E.M.) Radiation				
	Temperature			Relative	Pressure			*Vibration		Acoustic	Unmounted Shock	Tilt (degree)		*Electromagnetic Field			Magnetic Fields	
	Min	Max	Rate /min	Humidity	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Flux Density Max	Rate/s
	(Celsius)			(% R.H.)	(kPa)			(Hz)	(g^2/Hz)	(dBc)	(g)	Degree	Degree /sec	(Hz)	(Vm-1 peak)	(Vm-1 r.m.s.)	G	G/s
8	-60	100	40	0-100	20	200	300	2000	0.0100	180	2000	360	1000	50G	10000	1000	>5000	1000
7	-50	90	30	0-85	30	180	200	1500	0.0086	165	1000	300	500	18G	5000	800	1000	500
6	-40	80	20	0-70	40	160	100	1000	0.0074	150	500	240	250	6G	1000	600	100	100
5	-30	70	10	15-90	50	150	50	500	0.0061	135	100	190	100	1G	500	400	50	50
4	-20	60	5	15-70	60	140	10	250	0.0049	120	50	140	50	100M	200	200	25	25
3	-10	50	1	30-95	70	130	5	100	0.0036	105	30	90	10	70M	100	100	10	10
2	1	40	0.1	30-70	80	120	1	50	0.0024	90	10	30	1	30M	50	50	5	5
1	10	30	0.01	30-50	90	110	0.1	10	0.0011	75	5	15	0.1	500k	10	10	1	1
0	18	22	0	35-45	100	101	0	5	0.0001	60	1	1	0	10k	1	1	0.5	0.5

(a)

Platform ESL	Climatic							Mechanical						Platform Induced Electromagnetic (E.M.) Radiation					
	Temperature			Relative	Pressure			*Vibration		Acoustic	Unmounted Shock	Tilt (degree)		*Electromagnetic Field			Magnetic Fields		
	Min	Max	Rate /min	Humidity	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Flux Density Max	Rate/s	
	(Celsius)			(% R.H.)	(kPa)			(Hz)	(g^2/Hz)	(dBc)	(g)	Degree	Degree /sec	(Hz)	(Vm-1 peak)	(Vm-1 r.m.s.)	G	G/s	
8				1															
7				1											1				
6				2							1				1				
5				2			1				1				1				
4		2	1	2			1	2			1				1			2	
3	2	2	2	2			1	2			1		2		1		2	2	
2	2	2	2	2	1	1	1	2		2	1	2	2		1		2	2	
1	2	2	2	2	2	1	2	2		2	1	2	2		2		2	2	
0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	
Platform operate ESL profile value	8	10	8	14	4	2	4	10	2	6	2	6	8	2	4	2	8	10	110
Platform survive ESL profile value	NA	NA	1	2	1	2	4	NA	NA	NA	6	NA	Na	NA	6	NA	NA	NA	22

(b)

Power Weight	*Internal-battery powered	*Platform-battery	*Generator powered	Mains powered
Lightweight and/or handheld	<1L, <0.5W, <1kg	<1L, 1-50W, <1kg		
Backpack sized, person-portable	1-10L, <1W, 1kg -10kg	1-11L, 1-50W, 1kg - 10kg	1-10L, 50-1000W, 1kg - 10kg	1-10L, >1kW, 1kg - 10kg
Rack mounted and vehicle portable	1-10L, <1W, 11kg - 50kg	11-100L, 1-50W, 11kg - 50kg	11-100L, 50-1000W, 11kg - 50kg	11-100L, >1kW, 11kg - 50kg
Heavy, platform-fixed	1-10L, <1W, 51kg - 100kg	11-100L, 1-50W, 50kg - 100kg	101-1000L, 50-1000W, 50kg - 100kg	101-1000L, >1kW, 50kg - 100kg
Very heavy, special mounting.			101-1000L, 50-1000W, <1000kg	>1000L, >1kW, <1000kg

(c)

Power Weight	*Internal-battery powered	*Platform-battery	*Generator powered	Mains powered
Lightweight and/or handheld				
Backpack sized, person-portable		4		
Rack mounted and vehicle portable		4		
Heavy, platform-fixed		3		
Very heavy, special mounting.				

(d)

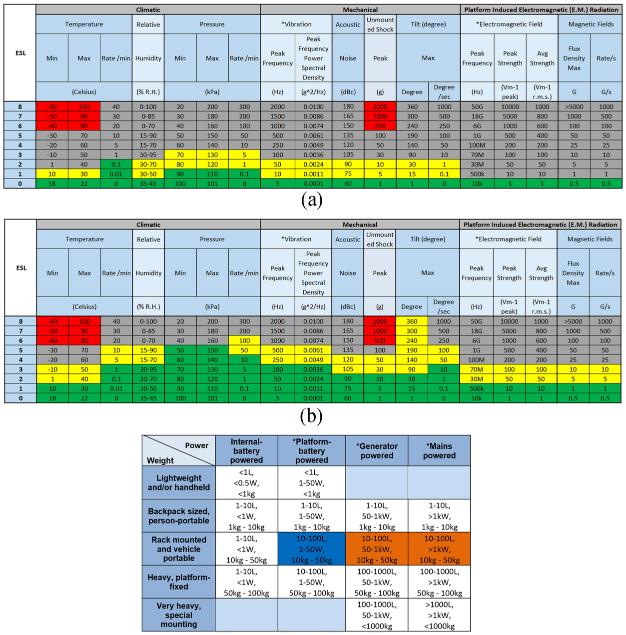
FIGURE 14. Platform B. (a) Platform ESL matrix. (b) ESL matrix with platform profiles (blue solid and dashed line) and profile values. (c) Platform SWaP matrix. (d) SWaP matrix profiles.

Colour Key	Technology Capability	Description	Assigned Value
Red	Inaccessible	The technology cannot survive these conditions under any circumstance due to practical/technological/fundamental reasons.	NA
White	Unknown	Best estimates should be given, but in cases where the response to the environment it truly unknown.	NA
Amber	Survivable	The technology has been demonstrated to **survive** under these conditions.	1
Green	Operational	The technology has been demonstrated to **operate** under these conditions.	2

FIGURE 15. Technology capability ESL matrix's color coding key.

Colour Key	Capability	Description	Assigned Value
Red	Impossible	By the fundamental nature of the technology, it cannot fit within the SWAP category.	NA
White	Unknown	Best estimates should be given, but in cases where their response to the environment is truly unknown in the future (5 years).	NA
Blue	Deliverable	The technology could be built within this constraint in the future (5 years).	3
Orange	Current	The current form factor of the technology.	4

FIGURE 16. Technology SWaP matrix's development profile color coding key.



ESL	Climatic							Mechanical						Platform Induced Electromagnetic (E.M.) Radiation				
	Temperature			Relative	Pressure			*Vibration		Acoustic	Unmounted Shock	Tilt (degree)		*Electromagnetic Field			Magnetic Fields	
	Min	Max	Rate /min	Humidity	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Flux Density Max	Rate/s
	(Celsius)			(% R.H.)	(kPa)			(Hz)	(g^2/Hz)	(dBc)	(g)	Degree	Degree /sec	(Hz)	(Vm-1 peak)	(Vm-1 r.m.s.)	G	G/s
8	-60	100	40	0-100	20	200	300	2000	0.0100	180	2000	360	1000	50G	10000	1000	>5000	1000
7	-50	90	30	0-85	30	180	200	1500	0.0086	165	1000	300	500	18G	5000	800	1000	500
6	-40	80	20	0-70	40	160	100	1000	0.0074	150	500	240	250	6G	1000	600	100	100
5	-30	70	10	15-90	50	150	50	500	0.0061	135	100	190	100	1G	500	400	50	50
4	-20	60	5	15-70	60	140	10	250	0.0049	120	50	140	50	100M	200	200	25	25
3	-10	50	1	30-95	70	130	5	100	0.0036	105	30	90	10	70M	100	100	10	10
2	1	40	0.1	30-70	80	120	1	50	0.0024	90	10	30	1	30M	50	50	5	5
1	10	30	0.01	30-50	90	110	0.1	10	0.0011	75	5	15	0.1	500k	10	10	1	1
0	18	22	0	35-45	100	101	0	5	0.0001	60	1	1	0	10k	1	1	0.5	0.5

(a)

ESL	Climatic							Mechanical						Platform Induced Electromagnetic (E.M.) Radiation				
	Temperature			Relative	Pressure			*Vibration		Acoustic	Unmounted Shock	Tilt (degree)		*Electromagnetic Field			Magnetic Fields	
	Min	Max	Rate /min	Humidity	Min	Max	Rate /min	Peak Frequency	Peak Frequency Power Spectral Density	Noise	Peak	Max		Peak Frequency	Peak Strength	Avg Strength	Flux Density Max	Rate/s
	(Celsius)			(% R.H.)	(kPa)			(Hz)	(g^2/Hz)	(dBc)	(g)	Degree	Degree /sec	(Hz)	(Vm-1 peak)	(Vm-1 r.m.s.)	G	G/s
8	-60	100	40	0-100	20	200	300	2000	0.0100	180	2000	360	1000	50G	10000	1000	>5000	1000
7	-50	90	30	0-85	30	180	200	1500	0.0086	165	1000	300	500	18G	5000	800	1000	500
6	-40	80	20	0-70	40	160	100	1000	0.0074	150	500	240	250	6G	1000	600	100	100
5	-30	70	10	15-90	50	150	50	500	0.0061	135	100	190	100	1G	500	400	50	50
4	-20	60	5	15-70	60	140	10	250	0.0049	120	50	140	50	100M	200	200	25	25
3	-10	50	1	30-95	70	130	5	100	0.0036	105	30	90	10	70M	100	100	10	10
2	1	40	0.1	30-70	80	120	1	50	0.0024	90	10	30	1	30M	50	50	5	5
1	10	30	0.01	30-50	90	110	0.1	10	0.0011	75	5	15	0.1	500k	10	10	1	1
0	18	22	0	35-45	100	101	0	5	0.0001	60	1	1	0	10k	1	1	0.5	0.5

(b)

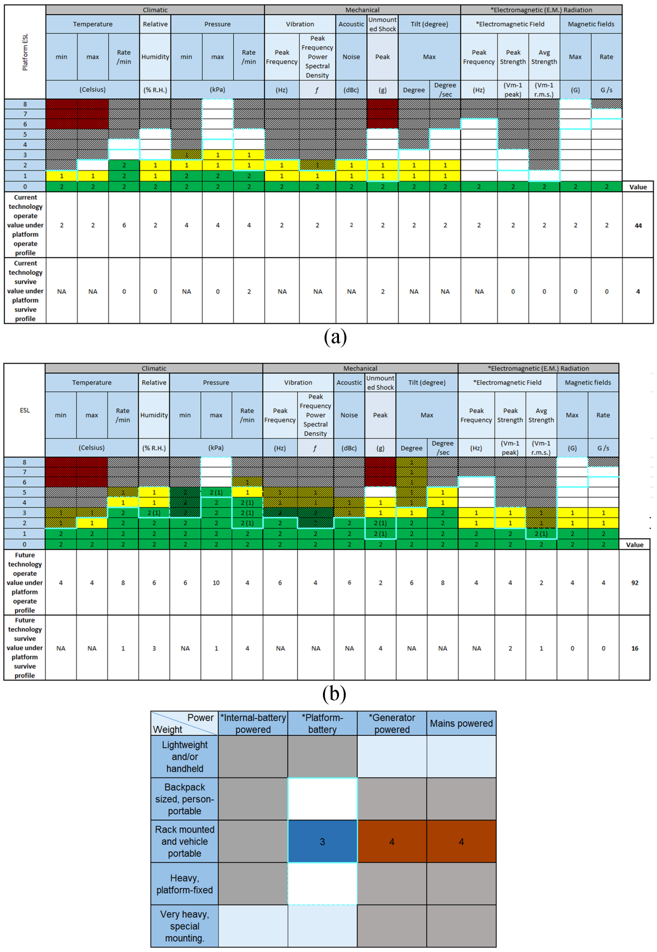
Power Weight	Internal-battery powered	*Platform-battery powered	*Generator powered	*Mains powered
Lightweight and/or handheld	<1L, <0.5W, <1kg	<1L, 1-50W, <1kg		
Backpack sized, person-portable	1-10L, <1W, 1kg - 10kg	1-10L, 1-50W, 1kg - 10kg	1-10L, 50-1kW, 1kg - 10kg	1-10L, >1kW, 1kg - 10kg
Rack mounted and vehicle portable	1-10L, <1W, 10kg - 50kg	10-100L, 1-50W, 10kg - 50kg	10-100L, 50-1kW, 10kg - 50kg	10-100L, >1kW, 10kg - 50kg
Heavy, platform-fixed	1-10L, <1W, 50kg - 100kg	10-100L, 1-50W, 50kg - 100kg	100-1000L, 50-1kW, 50kg - 100kg	100-1000L, >1kW, 50kg - 100kg
Very heavy, special mounting			100-1000L, 50-1kW, <1000kg	>1000L, >1kW, <1000kg

(c)

FIGURE 17. Technology capability. (a) Current environmental functional capability ESL matrix. (b) Future environmental functional capability ESL matrix. (c) Technology's SWaP matrix.

C. Q-PNT TECHNOLOGY MAP ANALYSIS

The defense and security sectors face the additional challenge when developing technology of releasing sanitized information in open literature while retaining necessary technical details. Two worked examples are presented to demonstrate how the ESL methodology can sanitize such information and provide suppliers with information on the suitability of technology to classified requirements. In these examples, the technology's required performance is used to define "operate" and "survive" functional modalities. For the SWaP matrix, each cell where a technology capability matches a platform requirement is considered an exact match in the MAP-SWaP process. The MAP process uses the requirements captured for platform



(a)

Platform ESL	Temperature min (Celsius)	Temperature max (Celsius)	Temperature Rate /min (Celsius)	Relative Humidity (% R.H.)	Pressure min (kPa)	Pressure max (kPa)	Pressure Rate /min (kPa)	Vibration Peak Frequency (Hz)	Vibration Peak Frequency Power Spectral Density (f)	Acoustic Noise (dBc)	Unmounted Shock Peak (g)	Tilt (degree) Max Degree	Tilt (degree) Max Degree /sec	*Electromagnetic Field Peak Frequency (Hz)	*Electromagnetic Field Peak Strength (Vm-1 peak)	*Electromagnetic Field Avg Strength (Vm-1 r.m.s.)	Magnetic fields Max (G)	Magnetic fields Rate G /s	
8																			
7																			
6																			
5																			
4																			
3					1	1	1												
2			2	1	1	1	1	1	1	1	1	1	1						
1	1	1	2	1	2	2	2	1	1	1	1	1	1						
0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	Value
Current technology operate value under platform operate profile	2	2	6	2	4	4	4	2	2	2	2	2	2	2	2	2	2	2	44
Current technology survive value under platform survive profile	NA	NA	0	0	NA	0	2	NA	NA	NA	2	NA	NA	NA	0	0	0	0	4

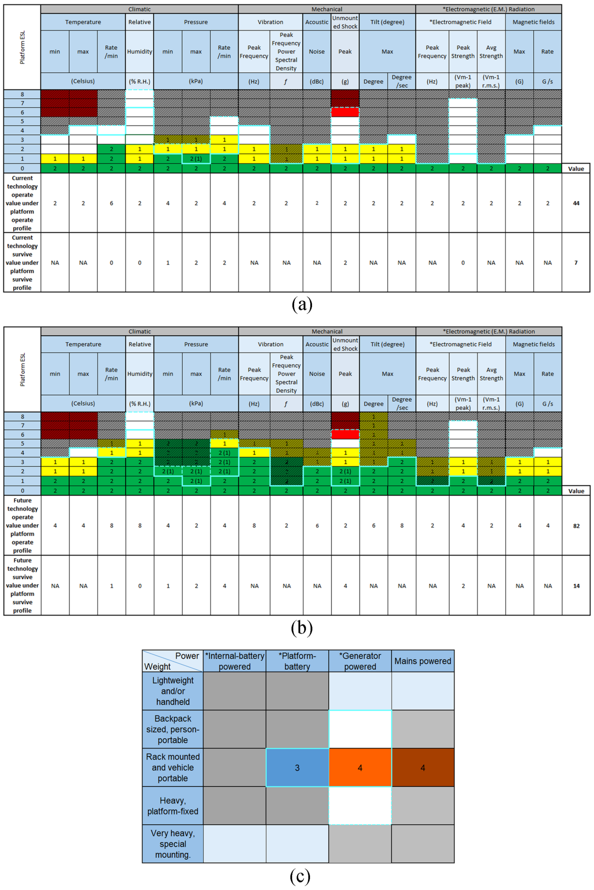
(b)

ESL	Temperature min (Celsius)	Temperature max (Celsius)	Temperature Rate /min (Celsius)	Relative Humidity (% R.H.)	Pressure min (kPa)	Pressure max (kPa)	Pressure Rate /min (kPa)	Vibration Peak Frequency (Hz)	Vibration Peak Frequency Power Spectral Density (f)	Acoustic Noise (dBc)	Unmounted Shock Peak (g)	Tilt (degree) Max Degree	Tilt (degree) Max Degree /sec	*Electromagnetic Field Peak Frequency (Hz)	*Electromagnetic Field Peak Strength (Vm-1 peak)	*Electromagnetic Field Avg Strength (Vm-1 r.m.s.)	Magnetic fields Max (G)	Magnetic fields Rate G /s	
8												1							
7												1							
6							1					1							
5			1	1	2	2 (1)	1	1	1			1	1						
4			1	1	2	2	2 (1)	1	1	1	1	1	1						
3	1	1	2	2 (1)	2	2	2 (1)	2	2	1	1	1	2	1	1	1	1	1	
2	1	1	2	2	2	2	2 (1)	2	2	2	2 (1)	2	2	1	1	1	1	1	
1	2	2	2	2	2	2	2	2	2	2	2 (1)	2	2	2	2	2 (1)	2	2	
0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	Value
Future technology operate value under platform operate profile	4	4	8	6	6	10	4	6	4	6	2	6	8	4	4	2	4	4	92
Future technology survive value under platform survive profile	NA	NA	1	3	NA	1	4	NA	NA	NA	4	NA	NA	NA	2	1	0	0	16

(c)

Weight \ Power	*Internal-battery powered	*Platform-battery	*Generator powered	Mains powered
Lightweight and/or handheld				
Backpack sized, person-portable				
Rack mounted and vehicle portable		3	4	4
Heavy, platform-fixed				
Very heavy, special mounting.				

FIGURE 18. **MAP analysis of technology to platform A. (a) Current technology capability ESL matrix with platform A profiles mapped (in blue) and MAP values deduced. The image shows that the current technology capability does not match the majority of the platform requirements identified by the white areas within the ESL matrix under the platform profiles. (b) Future technology capability ESL matrix with platform A profiles (blue) mapped and MAP values deduced. The image shows that the technology capability has increased and meets a greater number of the platform's environmental requirements. (c) Technology's SWaP matrix with platform A profiles, mapped in blue. The image shows that the current technology SWaP (orange cells) does not match that of the platforms. However, the blue cell identifies that the future technology SWaP will match the platform SWaP requirement.**



(a)

Platform ESL	Temperature min (Celsius)	Temperature max (Celsius)	Temperature Rate /min (Celsius)	Relative Humidity (% R.H.)	Pressure min (kPa)	Pressure max (kPa)	Pressure Rate /min (kPa)	Vibration Peak Frequency (Hz)	Vibration Peak Frequency Power Spectral Density (f)	Acoustic Noise (dBc)	Unmounted Shock Peak (g)	Tilt (degree) Max Degree	Tilt (degree) Max Degree /sec	*Electromagnetic Field Peak Frequency (Hz)	*Electromagnetic Field Peak Strength (Vm-1 peak)	*Electromagnetic Field Avg Strength (Vm-1 r.m.s.)	Magnetic fields Max (G)	Magnetic fields Rate G /s	
8																			
7																			
6																			
5																			
4																			
3					1	1	1												
2			2	1	1	1	1	1	1	1	1	1	1						
1	1	1	2	1	2	2 (1)	2	1	1	1	1	1	1						
0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	Value
Current technology operate value under platform operate profile	2	2	6	2	4	2	4	2	2	2	2	2	2	2	2	2	2	2	44
Current technology survive value under platform survive profile	NA	NA	0	0	1	2	2	NA	NA	NA	2	NA	NA	NA	0	NA	NA	NA	7

(b)

Platform ESL	Temperature min (Celsius)	Temperature max (Celsius)	Temperature Rate /min (Celsius)	Relative Humidity (% R.H.)	Pressure min (kPa)	Pressure max (kPa)	Pressure Rate /min (kPa)	Vibration Peak Frequency (Hz)	Vibration Peak Frequency Power Spectral Density (f)	Acoustic Noise (dBc)	Unmounted Shock Peak (g)	Tilt (degree) Max Degree	Tilt (degree) Max Degree /sec	*Electromagnetic Field Peak Frequency (Hz)	*Electromagnetic Field Peak Strength (Vm-1 peak)	*Electromagnetic Field Avg Strength (Vm-1 r.m.s.)	Magnetic fields Max (G)	Magnetic fields Rate G /s	
8												1							
7												1							
6							1					1							
5			1	1	2	2	1	1	1			1	1						
4			1	1	2	2	2 (1)	1	1	1	1	1	1						
3	1	1	2	2	2	2	2 (1)	2	2	1	1	1	2	1	1	1	1	1	
2	1	1	2	2	2 (1)	2 (1)	2 (1)	2	2	2	2 (1)	2	2	1	1	1	1	1	
1	2	2	2	2	2	2 (1)	2	2	2	2	2 (1)	2	2	2	2	2	2	2	
0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	Value
Future technology operate value under platform operate profile	4	4	8	8	4	2	4	8	2	6	2	6	8	2	4	2	4	4	82
Future technology survive value under platform survive profile	NA	NA	1	0	1	2	4	NA	NA	NA	4	NA	NA	NA	2	NA	NA	NA	14

(c)

Weight \ Power	*Internal-battery powered	*Platform-battery	*Generator powered	Mains powered
Lightweight and/or handheld				
Backpack sized, person-portable				
Rack mounted and vehicle portable		3	4	4
Heavy, platform-fixed				
Very heavy, special mounting.				

FIGURE 19. **MAP analysis of technology to platform B. (a) Current technology capability ESL matrix with platform B profiles mapped (in blue) and MAP values deduced. The image shows that the current technology capability does not match the majority of the platform requirements identified by the white areas within the ESL matrix under the platform profiles. (b) Future technology capability ESL matrix with platform B profiles (blue) mapped and MAP values deduced. The image shows that the technology capability has increased and meets a greater number of the platform's environmental requirements. (c) Technology's SWaP matrix with platform B profiles, mapped in blue. The image shows that the current technology SWaP (orange cells) matches the platform requirement and that the future technology SWaP overmatches.**

Platform	Current technology maturity to meet platform requirement				Future technology maturity to meet platform requirement			
	Operate environmental requirements	Survive environmental requirements	**Overall to meet platform environmental requirements**	SWaP requirements	Operate environmental requirements	Survive environmental requirements	**Overall to meet platform environmental requirements**	SWaP requirements
A	34%	17%	**26%**	100%	72%	67%	**70%**	100%
B	40%	*32%	***36%**	0%	75%	*64%	***70%**	*100%

FIGURE 20. **Summary of ESL and SWaP Map process analysis. The image shows that the technology's current environmental capability matches platform A's requirements by 26% and platform B's by 36%. The image also shows that the predicted future technology matches platforms A and B's environments by 70%. However, it has been shown that the technology is fundamentally limited within platform B's environment and does not meet the platform requirements.**

A (see Fig. 13) and B (see Fig. 14) to assess technology readiness. Fig. 18 and Fig. 19 present the results of the MAP-ESL and MAP-SWAP processes for platform A and platform B, respectively. The ESL matrices are normalized in areas where the technology's environmental functional capability overmatches the platform requirements, downgrading the operational functionality from value two to survive functionality of value one.

D. TECHNOLOGY READINESS ASSESSMENT SUMMARY

The ESL and SWaP matrices were used to capture the two platforms' technology requirements, enabling the articulation of the technology's environmental functional capabilities concerning the platforms' requirements. The MAP process was applied to quantify the technology's percentage fit to each platform. A summary of the data generated is presented in Fig. 20.

The figure shows that the technology's current environmental capability matches 26% of platform A's requirements and 36% of platform B's requirements. The predicted future technology matches the environments of both platforms by 70%, but Fig. 20 shows that the technology is fundamentally limited within platform B's environment and does not meet the platform requirements.

For both platforms, the current technology is TRL+ 4, and the future technology readiness is predicted to be TRL+ 5, as the technology capability and SWaP surpass 50% of the ESL and SWaP matrixes requirements. For platform A, the current technology SWaP capability matches one of the platform SWaP requirement options, making it an ideal match for the platform. For platform B, the current technology SWaP capability does not match any of the platform SWaP requirement options, but the proposed future SWaP of the technology directly matches one of the platform SWaP requirements.

The ESL matrix and MAP process identified that the technology is unsuitable for platform B due to the platform's unmounted shock survival requirement. Further investigation was carried out to assess supportive interventions and their impact on the device's SWaP to avoid a future roadblock. The tools and methodology applied highlighted a significant disparity between the two platforms, with the proposed research increasing the technology's readiness for platform A by 44% and for platform B by 36%. The results suggest that further research and development should aim to increase the technology's environmental functional capability, particularly in robustness to platform climatic change, unmounted shock, tilt, and electromagnetic radiation.

E. TOOL USABILITY EVIDENCE

For a methodology to be successful, it must be easy to use and provide a unique and impactful capability.

The Q-PNT research call invited suppliers to submit research proposals that supported the development of the next generation of PNT capability. These proposals included developing novel concepts and prototype hardware, testing commercially available off-the-shelf hardware, and developing sensor models. Prior to the release of the QPNT research call, no information on the ESL methodology was externally released from Dstl. Therefore, the first time suppliers were exposed to the methodology was through the information released in the research call.

A panel of DASA SME assessors deemed nine proposals involving the development of hardware prototypes fundable. Of these, seven correctly used the ESL and SWaP matrix tools within their proposals to articulate technology capability. Hence, 78% of suppliers correctly used the ESL methodology tools without prior knowledge or training.

F. GLOBAL OUTLIER IDENTIFICATION

The ESL matrix provided a simplified visual representation of platform requirements or technology capabilities. During the Q-PNT research call, two proposals, referred to as proposals X and Y, stood out as potential point anomalies. The proposal X proposed a prototype with much greater initial environmental robustness than anticipated, while the proposal Y proposed a significantly higher technology capability increase over a five-year time frame than other proposals.

Quantitative analysis was conducted on all received proposals to investigate these anomalies. The current and future technological operational capability profile values were deduced and compared. In addition, the proposals were also compared to the ten platforms' operational requirement profile values.

The proposal X had the highest initial technological operational capability value but the lowest increase in overall operational capability values over the five-year period. The proposal Y had an average initial technological operational capability value, but the greatest increase in technological operational capability value over the five-year period. The SWaP fit of the prototype to the platform SWaP requirement was also considered. Proposals X and Y had an MAP-SWaP analysis that fit both the current and future SWaP platform requirements, while the other proposals, on average, only met the SWaP platform requirements with the future proposed technology.

The three rational explanations for global outliers within the investigation are as follows.

1) *Inadequate ESL matrix:* One possible reason for global outliers is that the ESL matrix used in the investigation did not adequately capture space-based or high-velocity platforms. If a technology is designed to be highly robust in extreme environments, it may appear as a global outlier when compared to technologies intended for more benign platforms. In this case, the ESL matrix would fail to account for the specific requirements and capabilities of these outlier technologies.
2) *Incorrect data input:* Another plausible explanation is that the data entered into the ESL matrix were inaccurate or flawed. This could lead to an inaccurate assessment of the technology's performance and result in it being flagged as a global outlier.
3) *Developer overconfidence bias:* The third explanation is related to developer's overconfidence bias. In some instances, the investigation found that the anomaly was primarily caused by developers' overconfidence in their technology's capabilities. The proposals submitted for the research call met the requirement of being at TRL 4–6, but the ESL methodology revealed that in one instance, a proposal had a high probability of overconfidence bias.

   Identifying and addressing this bias is challenging as there are currently limited tools available to effectively detect and mitigate overconfidence bias in such evaluations.

IV. CONCLUSION

This article summarizes the challenges of using the TRL classification for assessing technological development and presents alternative methods to overcome its shortcomings.

One of the significant challenges of the TRL classification is its subjectivity and lack of linkage to real-world outcomes, making it difficult to quantify the technology readiness development life cycle and the resources, risks, and degree of difficulty to transition through TRLs. To address these challenges, a multifunctional technology-readiness classification approach and methodology were developed, which use platform environmental parameters and characteristics to quantitatively classify technology readiness as a function of technical capability within an operational environment.

The ESL methodology has been created to provide a simplistic and standardized process for developers to classify technology readiness as a function of a final real-world application. The ESL methodology has demonstrated rigor as a basis for redefining the TRL classification definitions, creating the TRL+. The DSTL Quantum Sensing Project has adopted the ESL methodology and TRL+ classification, which has shown the ability to articulate a technology's environmental functional capability and SWaP as a function of real-world use cases. The ESL methodology provided evidence to quantitatively classify current and projected technology development readiness and identify potential supplier overconfidence bias and early roadblocks for the future integration of technology into platforms.

The proposed ESL technology readiness assessment methodology is easy to understand and relies on factors other than technology SMEs having deep knowledge of platform requirements for operational environments. It can effectively communicate technology maturation to collaborators, project managers, and investors in a single visual form, facilitating the identification of areas that can be developed, technology mismatches, or early roadblocks to avoid wasteful time and expenditure. The methodology has highlighted specific areas of research and development that would have the most benefit in producing a functional technology, enabling project managers and investors to allocate resources and assess associated risks for transitioning the technology through TRL+ readiness levels.

The ESL methodology has demonstrated its potential to improve technology development time frames and return on investment. Further development could enable more widespread use of the approach to support project requirement setting, technical proposal comparison, and project compliance.

The ESL matrix is hardware-centric, and it is recommended that the methodology of capturing requirements and capability in a single dataset be tailored to support the development of algorithms and software.

Currently, no evaluation tool or methodology exists to quantify the degradation of technical performance as a function of the operational environment. It is recommended that the technical performance of the technology be represented in terms of technical accuracy as a value score to understand the degradation within a system over time and provide a complete picture of technology's true readiness in the intended environment.

A validation method for confirming the reliability of the ESL methodology could be investigated to enhance its effectiveness in technology readiness assessment. Future research should focus on conducting validation studies exploring pairwise comparison or the analytical hierarchy process to ensure consistency and objectivity in the assessment results. These methods can provide a more systematic and rigorous approach for comparing and prioritizing different factors or criteria.

The ESL methodology could be further developed to support requirements setting, technology development validation, and verification compliance of project delivery by integrating a standardized testing regime. A testing criteria range that incorporates laboratory to platform testing and links to the defense environmental handbook testing regimes and military specifications commonly used within the industry could be established. By developing a standardized ESL test and evaluation methodology, international efforts to overcome current challenges in developing next-generation sensors to operate outside of a laboratory environment could be unified in the context of developing quantum sensors.

In conclusion, the TRL classification has limitations in assessing technology development, and alternative methods have been developed to overcome its shortcomings. The proposed ESL technology readiness assessment methodology offers a simplistic and standardized approach for quantitatively classifying technology readiness as a function of a final real-world application, providing evidence to allocate resources and assess associated risks for transitioning technology through TRL+ readiness levels. Further development of the methodology could enable more widespread use and support project requirement setting, technical proposal comparison, and project compliance. The methodology has demonstrated potential in improving technology development time frames, particularly in the defense and security sector, by overcoming additional challenges faced due to the classified nature of technical information on use-case environments.

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