Engineering Severity Level - A quantitative technology maturity assessment tool

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Engineering Severity Level - A quantitative technology maturity assessment tool

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Index Terms—maturity level, prototype development, quantum technology, systems engineering, technology assessment, technology readiness level, technology development, technology maturity, TRL

I. INTRODUCTION

When is the right time to invest in fundamental research? Moreover, what specific areas should be supported to ensure that the technology developed is suitable for market needs? These questions exercise the minds of industry sectors, government bodies, and financial investors alike. Early-stage decisions like these can mean the difference between world-leading capability emerging first to the marketplace, technical roadblocks becoming a sink for investment, or end-products needing to be more robust in ensuring sufficient returns on investment.

To allow developers and investors to make informed decisions and target resources efficiently, they need to be able to evaluate the extent of the scientific limit relative to the practical limit of operation within a real-world scenario. This challenge highlights the principal requirement to accurately define technology developmental stages to drive and track technology maturity.

Assessing technology maturity accurately and efficiently has been a focal point of research that predates the technology forecasting of the 1950s. However, a pinnacle moment occurred in the 1970s, when the National Aeronautics and Space Administration (NASA) derived the Technology Readiness Level (TRL) [1]. This was motivated by the need to assess technology readiness against requirements and communicate it across the organisation in a common language to highlight risk at critical developmental stages and promote testing and verification. Since its conception, governmental and commercial organisations have adopted the TRL classification system worldwide1. Its widespread proliferation is a testament to the tool’s utility. Yet, the tool was designed to meet the specific needs of NASA and out-of-context use has resulted in programme delivery shortfalls [2-6] and well-documented issues highlight the imperative need for a maturity tool that provides clear evidence for classifying technology maturity. However, the challenges in creating such a robust, standardised method of assessing technology maturity are reflected in the abundance of tools, matrices and indices available in the literature.

This paper introduce a conceptual technology maturity measurement tool, the Engineering Severity Level (ESL), created to overcome known challenges when developing a fit-for-purpose technology. The tool complements and enhances the TRL definition, which we refer to as the ‘TRL+’, thus creating a standardised and quantitative method of accurately assigning a maturity level. The information provided within this article serves as a starter guide for adoption and adaption by technology developers across government organisations, academia and industry sectors.

II. BACKGROUND

The NASA classification tool [1] has evolved with time and application. As a result, organisations have modified their version of the original classification and, in some cases, created additional classifications to tailor the tool to meet specific needs. Nevertheless, the core construct of the TRL classification is broadly agreed as: TRL 1-4 describes a concept’s development stages to a laboratory-based prototype demonstrator; TRL 5-8 involve validating the technology within more challenging environments as a progression to a real-world scenario; and TRL 9 is a fully developed and operational technology.

Many tools and guides have been made available to support developers in accurately classifying technology via the TRL2. Nevertheless, the TRL commonly relies on a technology being assessed by a Subject Matter Expert (SME) through

2 Most notable are the TRL calculator [8-9], assessment frameworks [10], TRL rubric [11], a US Government Accountability Office (GAO) Technical Readiness Assessment Guide [12], and an International Organization for Standardization (ISO) 16290:2013 standard for its application in the space domain.
predominantly subjective review. An abundance of reviews and quantitative assessments have been carried out on the utility of the TRL, and common challenge themes have been extensively reported, irrespective of supporting documentation and tools. Therefore, rather than further investigate challenges identified in modern TRL use, this paper builds upon previous studies to develop a new tool that supports overcoming the challenges and effectively manages the identifiable risks in developing novel technology.

When applying the TRL tool across the breadth of possible technology developments, agnostic of application or industry, the challenges identified can be summarised into four dominant contributing factors:

I. **TRL classification attempts to measure the readiness of technology against a generalised requirement to operate. However, it does not include functional aspects such as its ability to operate within a system or its capability to produce a real-world operational outcome, and it treats the technology as singular when it should represent more than the sum of its parts [13 – 17].**

II. Many aspects of the TRL classification are subjective, and understanding of the world and the inherent acceptance of risks vary vastly from person to person. For example, there is no standardised measure of operational physical environment from TRL 4 to 7 [18 – 19].

III. **Technology readiness does not necessarily reflect technology maturity timelines and does not capture development lifecycles required to transition up the scale. The scale is a rigid binary metric, lacking in functionality relative to changing expectations as time passes [13, 20 – 25].**

IV. **TRL classification supports identifying potential risk areas, but it does not provide a metric to assess the associated risk or the degree of difficulty in transitioning from one readiness level to another [6, 26-27].**

A complex combination of these factors, matched with overconfidence bias toward delivery performance capability [28-30], has been identified as the main contributing factor in documented cases of failed technology insertion [31-35]. An example of this is the development of the James Webb Telescope [36], where poor assessment and tracking of technology development transpired into a significant increase in forecasted resources and an exponential growth in programme timeframes.

Over the last thirty years, an abundance of supportive methods and alternatives have emerged to overcome these challenges, with one review finding 409 relevant papers on the subject [37]. These ideologies range from simple adaptations to the current TRL metric [38-39] or linking TRL to other standardised architecture frameworks [27]; to a plethora of readiness levels that incorporate TRL, each offering an improved ability to accurately assess technology maturity.

A significant advancement in technology development and the assessment of progression is the ability to mathematically quantify a technology’s maturity in terms of readiness of internal system integration between components, provided by Sauser’s System Readiness Level (SRL) [13] [41, 46]. Since the creation of the SRL, further developments have been made linking technology maturity with system-of-systems and systems engineering architectures. A non-exhaustive summary of relevant readiness levels and how they interconnect is presented in Fig. 1.

![Fig. 1. Summary of readiness level classification approaches and how they interlink in support of the development of technology and assessing maturity.](image)

The matrices, indices and assessments, shown in Fig. 1, have varying levels of complexity in their use, with the majority requiring an SME to interpret the information and assess the maturity of technology in relation to the final operational requirement. In many cases, the SME may not be suitably knowledgeable in both the science and the industrial application of a technology. An excellent example of this is the Cornford & Sarsfield Developmental Maturity Index (DMI) [40], created to use in place of TRL and link the system-of-systems approach to a set of subjective measurements. The DMI uses technology Key Engineering Performance Parameters (KEPPs) that are repeatedly assessed throughout the development cycle. This approach addresses the issue of technology maturity assessment by including developmental targets within the development cycle. However, these targets are unique for each component and require an SME to assign and negotiate the acceptance development cycle.

Technology developers are in a better position today to develop technology through the understanding of the maturity of a system-of-systems through these adopted tools and approaches. Moreover, improved computer modelling and ‘Digital Twins’ may provide quantifiable evidence, but they come with an inherent cost proportional to the reliability and complexity of models, which may become a limiting factor for technology development. Nevertheless, there is still a gap within industry and academia for a standardised, simple tool to quantify the overall technology capability against the final real-world operational requirement to objectively define technology maturity.

This paper outlines an investigation into creating such a tool to assess technology development maturity as a function of final operational requirements whilst also providing an evidence base for maturity classification. It is formed of two data capture tools, the Engineering Severity Level (ESL) matrix and the Size, Weight, and Power (SWaP) matrix, and a tool to correlate
the data sets against a specific application, the Mapping Associated Parameters (MAP) methodology. The combination of these tools generates a quantitative evidence base to accurately assess technology development stages and identify critical research and investment areas required to realise an operational technology for a specific application. The ESL tool can also be applied to the current TRL classification to redefine the level descriptions, creating the ‘TRL+’ classification, a standardised and quantitative metric for technology maturity assessment.

The following sections of this report provide a complete description of the ESL and SWaP matrices for both technology and the platform it is intended to operate within. The MAP process that quantifies the goodness-of-fit for that technology to said platform is then introduced and shown that it provides evidence for investment to improve the suitability of fit. A discussion follows on how these tools can complement and enhance the TRL tool. In Section V, a step-by-step example of using the tools within the emerging field of quantum technology and their use within demanding defence and security platforms is provided.

III. METHODOLOGY

In this section, we start by describing how the parameters and their ranges are defined within the ESL matrix (part A). Then, two versions of the ESL are completed: the ‘platform requirements’ matrix, which provides the conditions the technology must operate within (part B) and the ‘technology capability’ matrix, which highlights which conditions the technology can operate under (part C). The MAP process analyses include the technology capability and platform requirement matrices and provides a goodness-of-fit for the technology to a platform (part D). The exact process is followed for the SWaP matrices, as shown in part E.

A. Engineering Severity Level dataset matrix

A technology or system is required to function within a technical performance envelope in a platform over an operational period within a real-world environment. The term 'platform' describes any operating space or set of conditions the technology must withstand. The construct of an ESL matrix is shown in Fig. 2. It was generated to draw together disparate data sources, capture common platform environment parameters within a single dataset, and represent the range of platform environments in a common, understandable format. The severity of each parameter is indicated along the matrix column's vertical axis. In the example shown in Fig. 2, the ESL matrix values range from a benign laboratory environment, represented by zero along the bottom row, to a value, V, that captures the scale of the most extreme platform environments within which the technology is expected to operate.

The ESL matrix is designed to represent any environmental parameter, and the range and increments are user-definable to capture the necessary granularity of the operational environments. For this report, an investigation was carried out to evaluate military platform environmental parameters and characteristics. The data was captured from Defence Standards (Def Stans), military specifications, and real-world data. The investigation found that, irrespective of platform domain (land, sea or air) or platform type, the environment that technology or system is required to operate within could be defined by an array of physical conditions, with many being common across all platforms. The most common environmental parameters were: temperature, pressure, acoustic noise, vibration, and electromagnetic field characteristics. It was also found, that environmental parameter severity is a function of platform type, with large ships having relatively less severe conditions than a tank or rocket.

In a real-world scenario, a technology has to operate in a complex combination of environmental events over timescales relating to platform operation and service lifetime. Therefore, the values within the ESL matrix represent an approximated single independent event at a specific location within a platform. Nonetheless, this methodology can be applied to real-world scenarios as an ESL matrix represents a single dataset that captures a snapshot of approximated common platform environmental parameters. An example of a real-world ESL matrix created from the investigation is shown in Fig. 3.

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

B. Platform requirements ESL matrix

The function of technology is to provide a performance service that will a) continually operate throughout platform environments or b) survive extreme environmental events and promptly resume operating performance once returned to less severe environments. These modes of operation identified the need to distinguish between survivable and operational parameters. Operate in this context is defined as providing a performance within an accepted risk envelope. These requirements are captured in the ESL platform matrix by colour-coding the matrix cells that represent functional platform of operate (green) with a technical performance or survive (orange) with degraded or no technical performance. This is presented in Fig. 4.

![Fig. 2. ESL matrix example.](image-url)
Two profiles can be drawn to represent the platform’s maximum operate and survive environmental parameter values. One profile is identified as a solid line for the operate function, and another as a broken line for the survive function, as presented in Fig. 4. A weighted score is assigned to the platform’s operate and survive function requirements to reflect their relative importance. The weighted scores are used to carry out the MAP comparative best-fit quantitative analysis with technology capability, resulting in a ‘maturity percentage’ value for a technology. In the example shown in Fig. 4, the operate function is assigned a greater weighted value (two) than the survive requirement function value (one), as operating at an environmental parameter is a preferred capability over only surviving. However, there may be instances when technology is preferred to survive rather than operate in extreme environments, such as rocket launches.

The platform operate value is the summation of values under the platform operate profile (solid black line), and the platform survive value is the summation of values under the platform survive profile (broken black line) and above the platform operate line. In the example presented in Fig. 4, these values are 30 and 8, respectively and will be used within the MAP-ESL process given in part D.

C. Technology Capability ESL matrix

A technology’s ability to function in various environments is represented on a separate ESL matrix by applying the same method used to capture platform requirements. Hence, the technology’s operate (green) with a technical performance and survive (yellow) with degraded or no technical performance capabilities are identified on an ESL matrix, presented in Fig. 5. The technology’s environmental operate and survive functionalities must be assigned the exact weighting used within the platform requirement ESL matrix to allow for the MAP process. In this example, two has been assigned for operate and one for survive.

Additional information about the technology can be captured on the ESL matrix, such as conditions where the technology is unproven, highlighted grey in Fig. 5, or fundamentally cannot survive within, highlighted red in Fig 5. These additional technology attributes are not given a weighted score but are used to inform the tool user when completing the MAP process.

D. Mapping Associated Parameters (MAP)

At the core of the ESL tool is the ability to rapidly identify discrepancies or mismatches between technology parameters and platform requirements; this can be used to test hypotheses, target technological development, or trade non-key performance requirements for time or cost parameters.

The MAP numerical analysis derives a coarse percentage fit of the suitability of the technology’s environmental functional capability for the platform in question, with details showing opportunities for compromise and development. An example is shown in Fig. 6, in which the solid and dashed lines from the platform requirements ESL (Fig. 4) are overlaid on the technology capability ESL Fig. 5. The total number of green cell values under the platform operate profile (solid black line) is summed and compared with the platform operate profile value to yield a percentage fit. In the example in Fig. 5, the total green cell value is 16, and the platform operate profile value is 30 (Fig. 5). So the percentage fit of technology operate capability to platform operate requirement is (16/30) x100 = 53%. Similarly, the suitability percentage of the technology to meet the platform survive requirement is evaluated by summing the total values in each yellow cell that lies below the platform survive (a value of two in the example shown in Fig. 6) and above the platform operate profiles (a value of eight in the example shown in Fig. 6). Comparison of these values is made to calculate the coarse percentage fit of technology survive capability to platform operate requirement, in this example 25%.
Combining operate and survive suitability percentages deduces the overall technology suitability to platform environmental requirements. In this example, the overall suitability percentage is the average of 53% and 25%, so 39%.

E. Size, Weight and Power ESL process

Another significant factor for a technology to provide a platform functional role is the available Size Weight and Power (SWaP). The initial investigation identified the common platform SWaP constraints for integrated technology. These parameters can be represented as three variables within a single two-dimensional SWaP matrix dataset Fig. 7.

![SWaP matrix example](image)

In the example shown, the SWaP available for a technology is given within each cell, ranging from the most severe SWaP constraints in the top left matrix cell to the least severe in the bottom right matrix cell. The value of each cell is customisable for the user’s requirement and thus can be adapted for real-world scenarios, as presented in Fig. 8.

![Real-world SWaP matrix example](image)

For the MAP process, each SWaP cell is colour coded and assigned a weighted score to represent the current (orange, with value four in the example in Fig. 9) or potential (purple, with value two) aptitude of platform SWaP requirements. A solid black line is drawn around the perimeter of the cells spanning the current SWaP requirement. Similarly, a dashed black line is drawn around the perimeter of the cells spanning the potential platform SWaP requirement.

![Platform SWaP requirement matrix, with platform profiles where orange indicates current performance and purple potential performance. The solid and the dashed outlined boxes are the current and potential requirements.](image)

An example of a technology’s current SWaP is presented in Fig 10. Each SWaP attribute is assigned a numerical value identical to those used within the platform SWaP requirement matrix, as this allows for a direct comparison.

![Technology SWaP capability matrix.](image)

In creating the two matrices, the suitability of the technology SWaP capability to meet the platform requirement can be assessed via the MAP process, where the platform SWaP attribute profiles are overlaid onto the technology SWaP capability matrix, presented in Fig. 11.

![MAP-SWaP process. In example Fig. 11, the technology meets 100% of the current platform SWaP, but 0% of the future requirement.](image)

TRL REDEFINED

The ESL analysis method provides a simplistic common language that is easily accessible for targeting areas of interest to technology integrators, developers, and investors. It also provides an auditable evidence trail for technology development and acquisition, and can highlight contextual technology limits concerning real-world applications.

The ESL tool can be used as a standalone tool; however, it is proposed that the tool be applied as a standardised, universal quantitative basis within the TRL classification scheme to provide further context and evidence-base to the definitions. Example shown in Fig. 12.

![Example of TRL classification descriptions redefined using the ESL / SWaP matrices tools and MAP process methodology.](image)
The TRL+ESL (or simply TRL+) classification is based on the MOD TRL classification [49], but applies the ESL and SWaP matrices to redefine the definition of levels 4 to 8.

In the TRL definition, TRL 4 represents basic validation of a technology in a laboratory environment, without size, weight and/or power constraints. This is equivalent to the ESL 0 for each environmental parameter. For example, the temperature of a laboratory is 20°C, and pressure is standard atmospheric pressure 101kPa, as shown in the example ESL in Fig 3. 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.

At present, the environment and SWaP of TRL 5, 6, 7 and 8 are not quantitatively defined. However, applying the ESL and SWaP matrices, a quantitative and standardised metric can be defined within the TRL classification definition as:

- TRL+ 5 when demonstrating a set performance capability within a controlled environment that meets a minimum of 50% of a ESL platform environment requirement and a form factor and power capability matching a minimum of 50% of the SWaP requirement.

- TRL+ 6 when demonstrating a set performance capability within a controlled environment that meets a minimum 100% of a ESL platform environment requirement and with a form factor and power capability meeting a minimum of 50% of the SWaP requirement.

- TRL+ 7 when demonstrating a set performance capability within the intended operational environment that meets a minimum of 75% of a ESL platform environment requirement with a form factor and power capability meeting a minimum of 75% of the SWaP requirement.

- TRL+ 8 when demonstrating a set performance capability within the intended operational environment that meets 100% of a ESL platform environment requirement with a form factor and power capability meeting a minimum of 75% of the SWaP requirement.

Where the ESL architect sets the definition of a controlled environment. Examples of a controlled environment 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 manoeuvres.

The ESL tool is not intended to be used as a standalone systems engineering tool but as a standardised methodology for quantitatively assessing and defining technology maturity classification and identifying areas of R&D within the development process. However, applying the ESL tool to redefine the definitions within the TRL classification allows the TRL+ to be used alongside many of the abovementioned system engineering tools and classifications, shown in Fig. 1.

V. INVESTIGATION

Quantum 2.0 technology [50] is analogous to the transistor in that the application space is vast, and the potential impact on humanity is significant. Furthermore, the underlying science is complex, and maturing low TRL quantum technology comes with a substantial financial burden that reflects the world-leading expertise and facilities involved. Without evidence-based and targeted investment, developing such a breath of technology could escalate capability hype, development costs, and the resulting technology still being unfit for purpose.

The UK defence and security sector has demanding accurate and resilient Position, Navigation and Timing (PNT) requirements in terms of accuracy and resilience. When Global Navigation Satellite Systems (GNSS) are absent, denied, degraded, or unreliable, a platform’s Inertial Navigation System (INS) error will accumulate; PNT uncertainty will grow, and mission success may be compromised. The Dstl Quantum Sensing Project envisages that a route to a robust and enduring PNT solution will involve advancements in complementary military PNT technology with augmentation of current INS and next-generation quantum sensing capability. The following section details how the ESL methodology was trialled during a funding quantum-augmented PNT (Q-PNT) call from the Defence And Security Accelerator (DASA) – a MOD innovation funding body.

A. Q-PNT First Adopters

The Quantum Sensing Project identified ten first-adopter platforms for the Q-PNT investigation. These platforms represent a range of types from land, air, and sea domains with various operational complexities and PNT performance requirements. The environmental requirements for a technology to function within each platform were captured in ESLs, with the operate attribute being defined as a requirement for technology to meet the set performance 90% of the time, and the survive attribute to operate immediately once within the operate environmental parameter range. For the purpose of this paper, two first adopter platforms, platform A and platform B, have been chosen to demonstrate proof of concept of the new tool described. The platforms’ requirements and profile analyses are illustrated in Fig. 13a and 13b. The platforms are not identified due to the classified nature of this information, but this also demonstrated that the ESL tool provides a level of obfuscation that allows sensitive data to be processed without endangering security and privacy.
B. Q-PNT Investigation

A Quantum Sensing DASA research call “Reducing Reliance on Global Navigation Satellite Systems with Q-PNT” was released on 2nd November 2020. The research call focused on current sensing technology between TRL 4 to 6 [49], such as atomic clocks, quantum-enabled accelerometers, gyroscopes, gravity and magnetic field sensors. Research proposals were required to provide evidence in the form of six-month feasibility studies to support platform assertions of an advanced sensing performance or enhanced environmental operational capability in a five-year timeframe.

The suppliers were required to use the ESL and SWaP matrices to articulate the progression of the device’s physics package and driving devices from the current technical prototype to future (five-year) operational environmental capability. The ESL matrix, shown in Fig 3, and colour coding, shown in Fig. 15 was used. The SWaP matrix, shown in Fig. 8, and colour coding shown in Fig. 19 was selected. Suppliers also commented against each technology ESL matrices regarding technical performance capabilities for environmental conditions, assuming a single but repeatable event per parameter. An example of a proposed technology’s current and future environmental capability is presented in Fig. 16a and 16b, respectively. The supplier name and comments have been removed to maintain confidentiality.

Research proposals also included information on the device’s current and future (five-year) SWaP on the SWaP matrix Fig. 5, using the colour coding indicated in Fig. 17. An example of a proposed technology’s current and future SWaP capability is presented in Fig 18.

C. Q-PNT Technology MAP analysis

One challenge the defence and security sectors face is releasing sanitised information, such as specific technical performance, platform type and name, in open literature while retaining necessary technical detail. Two worked examples are shown to
demonstrate the capability of the ESL tool to sanitise such information and provide a supplier information on the suitability of technology to otherwise classified requirements.

In this instance, the performance of the technology is known and used to define the operate and survive functional modalities. When applying to the SWaP matrix, each cell that a technology capability matches to a platform requirement is deemed an exact match in the SWaP-Map process.

The requirements captured for platform A (Fig. 13) and platform B (Fig. 14.) were used to carry out the MAP process to assess technology maturity. The result of the MAP-ESL and MAP-SWaP process is presented in Fig. 19, for platform A and Fig. 20, for platform B. Areas in the ESL matrices where the technology’s environmental functional capability overmatched the platform requirements were normalised: e.g. downgrading the operational functionality of value two to survive functionality, value one.

The requirements captured for platform A (Fig. 13) and platform B (Fig. 14.) were used to carry out the MAP process to assess technology maturity. The result of the MAP-ESL and MAP-SWaP process is presented in Fig. 19, for platform A and Fig. 20, for platform B. Areas in the ESL matrices where the technology’s environmental functional capability overmatched the platform requirements were normalised: e.g. downgrading the operational functionality of value two to survive functionality, value one.

**Fig. 19.** 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.

**Fig. 20.** 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.

**D. Technology maturity assessment summary**

The two platform's technology environmental requirements were captured using the ESL and SWaP matrices, allowing the technology's environmental functional capabilities to be articulated as a function of the platform’s requirements. Finally, the MAP process was applied to quantify the technology’s percentage fit to each platform. The summary data is presented in Fig. 21.

*Technology is fundamentally limited to survive the platform’s unmounted shock environment without intervention that could increase future SWaP.*

**Fig. 21.** 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 platform A and B’s environments by 70%. However, it has been shown (Fig. 20) that the technology is fundamentally
limited within Platform B’s environment and does not meet the platform requirements.

For the MAP analysis, it can be identified that for both platforms A and B, the current technology is TRL+4, as the ESL capability is greater than 25% of the set ESL requirement. Additionally, the analysis has identified that the future technology maturity for both platforms is predicted to be TRL+5, as the technology capability and SWaP surpass 50% of the ESL and SWaP requirements.

Further information can be drawn from the MAP analysis. For Platform A the SWaP capability matches one of the current platform SWaP requirement options; hence, the current technology is an ideal match for the platform. The user can, at this point, make an informed decision to either request that the supplier progress or hold further research proposed to produce the future technology of lower SWaP. In the case of platform B, the current technology SWaP capability does not match any of the current platform SWaP requirement options, but the proposed future SWaP of the technology directly matches one of the platform SWaP requirements.

In each example, the technology appears similarly mature for both platforms. However, the tools and methodology applied highlight a significant disparity. For Platform A, it was deduced that the research proposed increases the technology’s maturity for the platform by 44%. Where for platform B, the increase is 36%. No further development was required to reduce the SWaP of the technology for successful integration into platform A, emphasising that further research and development should be aimed at increasing the technology’s environmental functional capability. Most notably, robustness to platform climatic change, unmounted shock, tilt and electromagnetic radiation. The ESL matrix and MAP process identified that the technology was unsuitable for platform B, as it would not survive the platform’s unmounted shock survival requirement. With this knowledge, further investigation was carried out to assess supportive interventions and their impact on the device’s SWaP to avoid a future roadblock.

E. Tool usability evidence

If a tool is 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 generation after next PNT capability. Those proposals received included developing novel concepts and prototype hardware, testing Commercially of the Shelf (CotS) hardware and developing sensor models. Prior to the release of the Quantum augmented PNT research call, no information on the ESL tool was released externally to Dstl. Hence, the first time suppliers were exposed to the tool was through the information released in the research call. Nine proposals involved the development of hardware prototypes and were deemed fundable by a panel of DASA SME assessors. Of these, seven correctly used the ESL tool within their proposals to articulate technology capability. Hence, 78% of suppliers correctly used the ESL tool without prior knowledge or training.

F. Global outlier identification

The ESL matrix provided a simplistic visual representation of a platform requirement or technology capability. From the Q-PNT research call, three research proposals stood out as potential point anomalies, appearing significantly different from others received. Proposals two and three were joint tenders that articulated a combined research effort with one current and one future technology capability ESL matrix, shown in Fig. 22. Proposal number five was a single research proposal with a current and future technology capability ESL matrix, shown in Fig. 23. In comparison of these proposals, an example of a typical current and future technology ESL matrix is shown in Fig. 16.

Fig. 22. Joint proposals 2 and 3 a. current and b. future technology capability matrices, where the technology’s ability to operate within an environment is coded green and survive yellow.

Fig. 23. Proposal 5’s a. current and b. future technology capability matrices, where the technology’s ability to operate within an environment is coded green and survive yellow.

Proposals two and three articulated in the ESL matrix (Fig. 22) were identified as point anomalies as the research proposed developed a TRL 4–6 prototype, but the current technology capability ESL matrix indicated that the prototype had a much greater environmental robustness than anticipated. Similarly, the future technology capability ESL matrix indicated a technology with significant robustness to extreme
environments. Proposal five (Fig. 23) was also identified as a point anomaly as the technology capability increase over a five-year timeframe was significantly greater when compared to the other research proposals. To investigate the visually identified point anomalies, quantitative analysis was carried out on all of the received proposals. The proposed current and future technology operate capability profile values were deduced for each proposal by summing the values assigned to each node within the ESL matrix (Fig. 24). The current and future technology operate capability profile values were compared to infer the increase over the five-year period (Fig. 24).

![Fig. 24](image)

The image shows each technology’s current and future operate capability profile values.

Proposals two and three indicated a technology with the highest overall initial technology operate capability, but the lowest increase in overall operate capability in a five-year period. Whereas, proposal five indicated an average initial technology operate capability, but the greatest increase in overall technology operate capability within the same timeframe. Assessing the absolute difference between research proposals only provided insight into point anomalies amongst tenders. Further information was drawn by comparing the current, and future technology operate capability ESL profile values (Fig. 24) with each of the ten platforms’ operate requirement profile values, shown in Fig. 25.

![Fig. 25](image)

Fig. 25. Platform operate requirement profile values.

From the percentage fit of proposed Q-PNT prototypes (TRL 4 to 6) to platform requirements (Fig. 26.), it has been shown that proposals one, four, five and combined proposals six and seven detail a technology that has an overall fit to first adopter platforms of between 30% to 75%. Whereas tenders two and three propose a current technology that overmatches all first-adopter platforms with an average of 181%. Similarly, the analysis also identifies that proposals one, four and combined proposals six and seven have an average future platform fit of between 79% and 107%. Whereas the combined proposals two and three and single proposal five have an average platform capability overmatch of 204% and 169%, respectively.

A final factor to consider was the SWaP fit of the prototype to the platform SWaP requirement. Proposals two, three and five indicated a SWaP MAP analysis that fit both the current and future SWaP platform requirements. In contrast, the other proposals, on average, only met the platform requirements with the future proposed technology. As each proposal detailed the development of novel technology, it was anticipated that the current technology SWaP capability would not directly match that of the platform requirement.

There are several plausible explanations for the global outliers identified. The ESL (Fig. 3) matrix used in the Q-PNT assessment represented air, land and sea platform environments. It does not capture environments of space-based platforms or high-velocity ballistic platforms. Hence, a technology indentified for these environments would appear as a point anomaly within the used ESL MAP assessment. Another underlying cause for a technology capability to appear as a global outlier is the incorrect assessment of a technology’s capability by a supplier. Potential reasons for this are a lack of understanding of the technology or overconfidence bias in the ability to deliver. In one instance described above, it was concluded that developer overconfidence bias was the dominant factor for the anomaly. At present, only a few, if any, tools provide an effective means for identifying this bias.

VI. DISCUSSION AND CONCLUSION

This paper gives a summary of the challenges faced when applying the TRL classification for assessing technology development. The predominant challenges were that the TRL tool: is subjective and does not link technology development to real-world outcomes, and does not provide a base to quantify the technology maturity development life cycle and the resources, risk and degree of difficulty to transition through TRLs. An abundance of supportive methods and alternatives has emerged to overcome these shortfalls. However, each has a varying level of complexity in their use, with the majority requiring an SME to interpret the information and all requiring an SME to assess the maturity of technology in relation to the final operational requirement. It was also highlighted that the defence and security sector has additional challenges in releasing use-case requirements to support technology maturity development due to the classified nature of the detailed requirements in association with the operational context. To overcome these challenges, an investigation was carried out to evaluate platform environmental parameters and characteristics. This information was used to develop a multifunctional technology-maturity classification approach and tool that quantifies developmental stages as a function of the technical capability within an operational environment.

The ESL and SWaP matrices and MAP process have been created as a simplistic and standardised tool to be used by developers to quantifiably classify technology maturity as a function of a final real-world application. In addition, the tool has demonstrated rigour as a standardised basis for redefining the TRL classification definitions, creating the TRL+.

The ESL tool and TRL+ classification have been adopted by DSTL Quantum Sensing Project and demonstrated an ability to...
articulate a technology's environmental functional capability and SWaP as a function of real-world use cases. The ESL tool provided the evidence to quantitatively classify current and projected technology maturity, via TRL+ classification, of a number of quantum technologies against first adopter platforms. Within this article, an example of one technology assessed against two platforms has been shown. In addition, the evidence produced by the ESL tool went beyond quantitatively classifying the maturity of technology by providing insight into potential supplier overconfidence bias and identification of an early roadblock for the future integration of the technology into one of the platforms, a realisation that would not have been attained without the ESL tool.

The proposed ESL technology maturity assessment tool does not contain jargon or vague terminologies, hence can articulate technology maturation to collaborators, project managers and investors in a single visual form. It does not rely on technology SMEs having deep knowledge of platform requirements or operational environments. Platform profiles either match or they do not; the areas that can be developed are easily identifiable; technology mismatches or roadblocks can be identified early, avoiding nugatory time and expense. Within the Q-PNT investigation, the ESL tool highlighted specific areas of research and development that would have the most benefit to producing a functional technology. With this information, the project manager and investor gain the evidence required to allocate the resources and assess associated risks for transitioning the technology through the TRL+ maturity levels.

The ESL and SWaP Matrix and MAP process have been shown to support overcoming the additional challenge faced by the defence and security sector in releasing technical information on use case environments without divulging classified information. This new approach has the potential to significantly improve technology development timeframes and return on investment within the Defence and Security sector if applied as a standardised metric.

Further development could enable more widespread use of the approach to support project requirement setting, technical proposal comparison, and project compliance. For example, the current ESL is hardware-centric; hence it is recommended that the methodology of capturing requirements and capability in a single dataset be retailed, but the parameters within the matrix be adapted to support the development of algorithms and software.

Currently, no evaluation tool exists to quantify the degradation of technical performance as a function of the operational environment. The ESL matrix is currently binary in that a technology’s environmental, operational functionality can be represented as either operate or survive, with context defined by the user. It is recommended that the technical performance of the technology be represented in terms of technical accuracy as a value score. For example, if a technology was able to meet the technical performance capability requirement 90% of the time, a maximum value of 10/10 could be awarded within the appropriate ESL matrix cell. If the technical performance capability was degraded at the next ESL increment and the technology could only meet 80% of that required, a score of 9/10 would be awarded. Illustrating technology in this way would be especially beneficial to understanding the degradation within a system over a period of time and providing a complete picture of a technology's true maturity in the intended environment.

The ESL tool methodology could be developed further to support requirements setting, technology development validation and verification compliance of project delivery by integrating a standardised testing regime. It is envisaged that testing criteria would have a range that incorporates laboratory to platform testing and should link to the Defence Environmental Handbook testing regimes and Mil-Spec that are commonly used within the industry. In the context of developing quantum sensors, realising a standardised ESL test and evaluation methodology could unify international efforts to overcome current challenges in developing next-generation sensors to operate outside of a laboratory environment.

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