The MultiRATE Holistic Readiness Level framework for civil security technologies

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RESEARCH ARTICLE

The MultiRATE Holistic Readiness Level framework for civil security technologies

[version 1; peer review: 2 approved with reservations]

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v1 **First published:** 13 Feb 2026, **6**:42
https://doi.org/10.12688/openreseurope.22711.1
Latest published: 13 Feb 2026, **6**:42
https://doi.org/10.12688/openreseurope.22711.1

Abstract

Background

The common use of the traditional Technology Readiness Level (TRL) scale in evaluating civil security technologies has revealed a significant problem: TRL, although a standard metric, is limited for complex innovations. It does not fully address risks and non-technical factors that are important for successful technological deployment. This creates a gap in assessment approaches, often referred to as the "Valley of Death" in innovation funding and technology transition. To address this, the MultiRATE Holistic Readiness Level (HRL) framework

Open Peer Review

Approval Status ? ?

	1	2
version 1 13 Feb 2026	? view	? view

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is introduced in this paper, aiming to provide a more comprehensive evaluation of civil security technology maturity.

Methods

Our method, developed within the EU-funded MultiRATE project, combines seven key readiness dimensions: TRL, Societal RL (SocRL), Security RL (SecRL), Legal, Privacy, and Ethics RL (LPERL), Integration RL (IRL), enhanced Commercialization RL (en-CRL), and Manufacturing RL (MRL), all adapted to the specifics of the security sector. Our approach, unlike the fragmented nature of existing individual readiness level assessments, provides a unified understanding of technology's readiness, including an investment forecasting module to estimate the costs for maturity progression.

Results

The MultiRATE HRL framework and its components were evaluated through a structured validation process with an external network of experts, following the Design Science Research Methodology (DSRM). This validation confirms the framework's feasibility and practical use in providing a more accurate assessment of security technology maturity.

Conclusions

MultiRATE provides a common language for researchers, end-users, and funding bodies, helping to de-risk the innovation process and bridge the "Valley of Death". The web-based MultiRATE HRL calculator is accessible at https://hrl.multiratehl.iti.gr.

Keywords
TRL, Holistic Readiness Level, Maturity Assessment, Research and Innovation, Civil Security Domain.

HE This article is included in the Horizon Europe gateway.

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Author roles: Unzueta L: Investigation, Methodology, Software, Writing – Original Draft Preparation; **Darra E**: Investigation, Methodology, Writing – Original Draft Preparation; **Kavallieros D**: Conceptualization, Investigation, Methodology, Writing – Original Draft Preparation; **Cadete G**: Investigation, Methodology, Validation, Writing – Original Draft Preparation; **Bates L**: Investigation, Methodology, Writing – Original Draft Preparation; **Hoog B**: Investigation, Methodology, Writing – Original Draft Preparation; **Grigoleit S**: Supervision, Writing – Review & Editing; **Adomaitis L**: Investigation, Methodology, Writing – Original Draft Preparation; **Grinbaum A**: Investigation, Methodology, Writing – Review & Editing; **Vicari S**: Investigation, Methodology, Software, Writing – Original Draft Preparation; **Sofou S**: Investigation, Methodology, Writing – Original Draft Preparation; **Chantavas N**: Investigation, Methodology, Writing – Original Draft Preparation; **Angelou M**: Data Curation, Investigation, Methodology, Software, Writing – Original Draft Preparation; **Vretos N**: Investigation, Methodology, Supervision, Validation, Writing – Review & Editing; **van der Lee M**: Investigation, Methodology, Validation, Writing – Review & Editing; **Toivonen S**: Validation, Writing – Review & Editing; **Peters C**: Investigation, Methodology, Validation, Writing – Review & Editing; **van Berlo M**: Supervision, Validation, Writing – Review & Editing; **Ríos D**: Conceptualization, Supervision, Writing – Review & Editing; **La Mattina E**: Supervision, Validation; **Essafi H**: Supervision, Validation; **Kostaridis A**: Supervision, Validation; **Diagourtas D**: Supervision, Validation; **Gibson H**: Investigation, Methodology, Validation, Writing – Review & Editing; **Akhgar B**: Conceptualization, Supervision, Validation; **Magime C**: Validation; **Åström A**: Validation; **Subeh Z**: Validation; **Tsikrika T**: Supervision, Validation; **Vrochidis S**: Conceptualization, Supervision, Validation; **Gaines S**: Conceptualization, Supervision, Validation

Competing interests: No competing interests were disclosed.

Grant information: This project has received funding from the European Union's Horizon Eu- rope research and innovation programme under grant agreement No. 101073929 (project name: Holistic framework for the MatUrity evaLuaTIon of ReAdiness level for security TEchnologies—MultiRATE).
The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

How to cite this article: Unzueta L, Darra E, Kavallieros D *et al.* **The MultiRATE Holistic Readiness Level framework for civil security technologies [version 1; peer review: 2 approved with reservations]** Open Research Europe 2026, **6**:42
https://doi.org/10.12688/openreseurope.22711.1

First published: 13 Feb 2026, **6**:42 https://doi.org/10.12688/openreseurope.22711.1

Introduction

For decades, the concept of Technology Readiness Levels (TRLs) has been fundamental in assessing the maturity of emerging technologies Mankins (1995). Originating within the National Aeronautics and Space Administration (NASA) in the 1970s to manage risk in complex space missions, the TRL scale provides a standardized language and metric system Sadin et al. (1989). TRL assesses the maturity of a particular technology on a nine-level scale, progressing from basic principles observed (TRL 1) through laboratory validation (TRL 4), demonstration in relevant and operational environments (TRL 6-7), system completion and qualification (TRL 8), up to the actual system being proven in its operational environment (TRL 9). Its primary purpose is to provide a common understanding of a technology's status, manage development risks, and inform decisions regarding funding allocation and the transition of the technology into systems or towards market deployment. Its utility led to widespread adoption by other major organizations, including the US Department of Defense (DoD), the European Space Agency (ESA), and notably, the European Union (EU) for its research and innovation funding programmes like Horizon 2020 and Horizon Europe, including the European Innovation Council (EIC) Héder (2017).

While widely used, the TRL scale has well-known limitations Olechowski et al. (2017), making it less effective for assessing complex systems or technologies with broad societal or market impacts. For instance, it does not sufficiently address the risks and complexities involved in integrating multiple technologies, including mature ones, into a larger system. Besides, it does not fully consider non-technical factors that are important for innovation deployment. Furthermore, it often does not adequately cover the transition phase between laboratory validation (typically TRL 4-5) and a market-ready system (TRL 8-9). This gap, often referred to as the "Valley of Death" Markham et al. (2010), corresponds approximately to TRLs 4-7, where funding and focus can be insufficient as technologies transition from academic research to private sector development. Holistic frameworks seek to address this by considering factors beyond technical proof-of-concept earlier in the development cycle.

Acknowledging the limitations of TRL, several additional Readiness Level (RL) dimensions have been suggested and, in certain instances, implemented to offer a more comprehensive assessment of an innovation's maturity and likelihood of successful deployment. These RL dimensions address critical non-technical factors such as the readiness of the human-system inter- face (Human Readiness Level, HRL) See (2021), integration (IRL) Sauser et al. (2008), the overall system (SRL) Sauser et al. (2006), manufacturing (MRL) Department of Defense (2023), commercialization, business, and market readiness (CRL, BRL, and again MRL) Gerdsri and Manotungvorapun (2021); Vik et al. (2021), societal acceptance (again SRL or SocRL) Stilgoe et al. (2013), acceptance and regulation (Acceptance RL, ARL, and Regulatory RL, RRL) Vik et al. (2021), organizational and legal alignment (Organizational RL, ORL, and Legal RL, LRL) Bruno et al. (2020), and even technology-specific dimensions such as AI Readiness Level (AIRL) and Data Readiness Level (DRL) for innovations where data is a key resource Eljasik-Swoboda et al. (2019). The development of these various RLs, in some cases with the same acronyms but for different concepts, has complicated the landscape, despite addressing TRL limitations. This "Tower of Babel" effect, with multiple terminologies, varying definitions even within the same RL type (e.g., different CRL scales Australian Renewable Energy Agency (2014); Gerdsri and Manotungvorapun (2021); Bruno et al. (2020)), diverse methodologies, and a lack of universal integration, presents challenges for consistent and efficient holistic assessment. Users must navigate this fragmented environment, potentially increasing the burden compared to the simplicity of the TRL scale Straub (2015).

Additionally, the quantitative aspiration suggested by the numerical scales used in most RL frameworks differs from the qualitative, evidence-based evaluations needed for non-technical fields like SocRL or CRL. This can lead to a false sense of precision or objectivity, masking underlying complexities and subjective judgments, and has led to critiques regarding the mathematical validity of combining ordinal scores Mankins (2009); Olechowski et al. (2017). Many of these complementary dimensions (e.g., Manufacturing RL, CRL, SocRL) incorporate external stakeholder interactions and feedback loops as key elements to show readiness Rip (2014); Stilgoe et al. (2013). This represents a shift from the internally focused technical demonstrations commonly associated with TRL assessment, indicating an understanding that effective innovation depends not only on internal R&D but also on alignment with the external ecosystem, market demands, and societal values.

In this context, the EU-funded MultiRATE project aims to create a holistic RL assessment framework to evaluate the holistic maturity of products, systems, or processes developed in civil security R&I projects for both Law Enforcement Agencies (LEAs) and non-LEAs. MultiRATE's white paper van der Lee et al. (2025) introduced its components, the design process that they were considering at the beginning of the project and discussed insights for its implementation. The RL dimensions include adapted versions of existing RL scales like TRL, SocRL, IRL, CRL, MRL (Manufacturing) as well as additional RL dimensions relevant in the field, such as Security RL (SecRL) and Legal, Privacy, and Ethics RL (LPERL) Adomaitis et al. (2024). All these dimensions needed to be holistically harmonized to meet the project's objectives. Additionally, the framework includes an investment forecasting module to estimate the costs required to increase RL maturity.

This paper elaborates on the implementation of this holistic framework and the evaluation of its feasibility by the project's conclusion. More specifically, the contributions of this work are the following:

- The MultiRATE Holistic Readiness Level (HRL) calculator that integrates the indicators and calculations from seven RL dimensions taking into account all their peculiarities adapted to the civil security sector. The web-based MultiRATE HRL calculator can be accessed here: https://hrl.multiratehl.iti.gr
- The adaptation and harmonization process to the security sector of the seven RL dimensions of the MultiRATE HRL: TRL, SocRL, SecRL, LPERL, IRL, en-CRL, and MRL.
- The integration process of an investment forecasting module to effectively estimate the costs required to increase RL maturity in the context of the MultiRATE HRL.
- The validation process of the MultiRATE HRL and its components with the collaboration of an external network of experts following the Design Science Research Methodology (DSRM) Peffers et al. (2007).

Related work

Setting up a conceptual framework that moves from a disjointed collection of independent one-dimensional RL scales toward an integrated, actionable, truly holistic viewpoint is still the main challenge in addressing the complex nature of innovation. Table 1 provides a comparative overview of the RL dimensions that form the building blocks of most prominent state-of-the-art holistic approaches.

The evolution of RL assessment beyond TRL can be seen as a series of reactive expansions, each designed to address a critical RL dimension over- looked by its predecessors Straub (2015). The development of SRL/IRL addressed technical system-level concerns, with a rigorous analysis of integration risks. However, its methods have been critiqued for performing arithmetic operations on ordinal data—ranked scales where the intervals are not uniform—which can create a false sense of precision Olechowski et al. (2017). Following with technology-specific needs, AIRL and DRL adapt readiness concepts for data-centric innovations where the quality and availability of data are paramount. Likewise, dimensions like ORL, LRL, and RRL emerged to assess readiness for deployment in complex organizational and regulatory environments, but their context-specific nature makes them difficult to apply proactively before policies are set.

On the other hand, the creation of Market RL and CRL/BRL expanded into the socio-economic sphere. These RL scales focus on market-pull and commercial viability, though the lack of a single standard for these can lead to subjective and inconsistent assessments. It is important to disambiguate MRL, as the acronym has been used to denote both Manufacturing Readiness Level, which provides a structured roadmap for de-risking production Department of Defense (2023), and Market Readiness Level, as defined within the Balanced Readiness Level assessment (BRLa) framework Vik et al. (2021). Henceforth, the acronym MRL will be used exclusively to denote Manufacturing RL.

Another expansion moved into the human and societal context. SocRL, Human RL, and Acceptance RL address public acceptance, usability, and user acceptance respectively, but all require significant qualitative analysis that can be difficult to standardize and resource-intensive to conduct. These complementary RL scales also share common challenges, as noted in Table 1, like that they are often resource-intensive, difficult to quantify, and lack universal standardization, motivating the development of holistic frameworks to manage their complexity.

Current state-of-the-art holistic frameworks can be broadly categorized by their primary philosophy, as reflected in Table 2. These frameworks offer different strategic approaches to holistic assessment. The US DoD's System Readiness Assessment (SRA), yielding an SRL, is a prime example of a "composite index" approach that attempts to create a single, unified score Sauser et al. (2006). For developing complex security systems, its strength is the rigorous focus on integration, which is critical for ensuring interoperability. However, its methodology of calculating a single, composite score has been critiqued for its use of arithmetic operations on ordinal data, which can obscure critical weaknesses in individual dimensions and may be less suited for the nuanced trade-offs required in security R&I Olechowski et al. (2017). In contrast, other frameworks focus on standardizing the assessment "process". The GAO's TRA guide, for example, offers a best-practice approach to carrying out TRAs and formulating Technology Maturation Plans for them U.S. Government Accountability Office (2020). To some extent, this is because it treats the process as an evidence-based,

Table 1. Comparison of RL dimensions, complementary to TRL, forming the basis of most prominent state-of-the-art holistic frameworks.

Framework	Primary focus	Strengths	Weaknesses
TRL Mankins (1995)	Technical feasibility of a single component.	Simple, ubiquitous, common language for technical maturity.	Ignores integration, manufacturing, market, and societal factors. Poor predictor of overall success.
SRL/IRL Sauser et al. (2006)	Technical feasibility and integration maturity of a system.	Forces rigorous architectural analysis and focus on interfaces.	Mathematically questionable (ordinal data), complex, lacks formal adoption outside defence/aerospace.
AIRL/DRL Eljasik-Swoboda et al. (2019)	Readiness of algorithms and data for AI/ML systems.	Adapts RL concepts for data-centric innovations, acknowledging data as a key resource.	Highly specific to a technology type, not an application domain; less standardized than other RLs.
ORL/LRL Bruno et al. (2020)	Organizational change management and legal/regulatory compliance.	Critical for deployment in regulated industries or public sector environments.	Highly context-specific; can be difficult to assess proactively before policies are set.
MRL Department of Defense (2023)	Producibility and manufacturing risk.	Structured roadmap for de-risking production; links engineering to manufacturing.	Resource-intensive, requires specialized expertise, limited adoption outside of defence/manufacturing.
Market RL /CRL/BRL Vik et al. (2021); Australian Renewable Energy Agency (2014); Gerdsri and Manotungvorapun (2021)	Commercial viability, market/ business case maturity, and commodification.	Focuses on market-pull and investment-potential from an early stage.	Lack of a single standard leads to inconsistency; can be subjective.
SocRL Stilgoe et al. (2013)	Societal acceptance, ethical implications, stakeholder engagement.	Addresses critical non-technical barriers to adoption for impactful technologies.	Can be highly subjective and difficult to quantify; newer and less validated than other RLs.
Human RL See (2021)	Human-system interaction, usability, and training.	Ensures technology is effective and safe in the hands of users, filling a major TRL gap.	Requires human factors expertise; can be subjective and resource-intensive to test properly.
Acceptance RL/RRL Vik et al. (2021)	User acceptance and regulatory/ legal alignment.	Addresses social and political aspects of innovation that can be major barriers to deployment.	The concepts are less standardized than others and are often highly context specific.

systematic one. However, it is not a multi-dimensional scale itself and remains heavily centred on the TRL metric, thereby not fully solving the problem of a narrow technical focus.

A third category, which most closely aligns with the philosophy of MultiRATE, involves context-specific "dashboards" that visualize multiple dimensions. These have been adapted for specific business contexts, technology types, and application domains. For instance, a framework designed for Innovation-Driven Enterprise (IDE) startups explicitly connects TRL and Manufacturing RL with Commercialization and Business RLs (CRL and BRL) to map a pathway toward sustainable growth Gerdsri and Manotungvorapun (2021). For assessing AI-based innovations, the READINESS-Navigator tool adapts the readiness concept by replacing MRL with specific AI and Data RLs (AIRL and DRL), acknowledging that data is the critical raw material Eljasik-Swoboda et al. (2019). The EU 4-Axis framework (TRL, SocRL, ORL, LRL) is another key example tailored to the application do- main of public sector innovation Bruno et al. (2020). While its inclusion of organizational and legal aspects is highly relevant, it omits the commercialization and manufacturing dimensions that are vital for ensuring a technology can be produced and sustained as a viable product. Similarly, the US Department of Energy's Adoption RL (ARL) framework is tailored to energy commercialization, focusing on a technology's value proposition and market acceptance U.S. Department of Energy (2023), and the Balanced Readiness Level Assessment (BRLa) uses generic dimensions (e.g., "Regulatory", "Acceptance") for agricultural technology that lack the specificity required for the security domain Vik et al. (2021). A notable example in the medical field is the Medical Device RL (MDRL) framework, which integrates Human RL concepts to assess not only technical function but also usability, comfort, and patient response van de Loo et al. (2022).

Finally, it is worth noting the existence of highly detailed holistic maturity models designed for the specific context of cybersecurity, such as the ENISA CSIRT framework European Union Agency for Cybersecurity (ENISA) (2019) and the Cybersecurity Capability Maturity Model (C2M2) U.S. Department of Energy (2022). Unlike the technology-focused frameworks in Table 2, these models assess the maturity of an entire "organization's" capabilities, processes, and security posture. Methodologically, they are instructive as they demonstrate how a complex domain can be broken down into granular components (e.g., C2M2's use of domains and objectives; ENISA's parameters for Organization, Human, Tools, and Processes) for detailed assessment. However, their purpose—assessing organizational posture—is

Table 2. Comparative overview of state-of-the-art holistic readiness frameworks.

Framework	Core purpose	Key dimensions assessed (beyond TRL)	Limitations/Critiques
Composite Index Approach			
SRA/SRL Sauser et al. (2006)	Assess system-level maturity and risk by combining technology and integration readiness.	IRL	Mathematical validity of combining ordinal data is questioned; potential for misleading results; still largely experimental.
Process-Focused Approach			
GAO TRA Guide U.S. Government Accountability Office (2020)	Standardize a high-quality, evidence-based process for conducting TRAs and managing risk.	Implicitly considers evidence quality, maturation planning.	Primarily a process guide, not a multi-dimensional RL scale itself; relies heavily on TRL as the core metric.
Context-Specific Dashboards			
EU 4-Axis Framework Bruno et al. (2020)	Assess the impact and potential of digital technologies for European public services.	SocRL, ORL, LRL	Proposed framework; needs validation outside digital public services; omits commercialization and manufacturing dimensions.
Adoption RL Framework U.S. Department of Energy (2023)	Assess non-technical commercialization risks and identify barriers to private sector uptake.	Value Proposition, Market Acceptance, Resource Maturity, License to Operate.	Specific to commercialization; may overlap with CRL/MRL; newer framework still gaining adoption.
BRLa Vik et al. (2021)	Provide a balanced, qualitative assessment of emerging technologies using a dashboard approach.	Market RL, RRL, Acceptance RL, ORL	A diagnostic tool, not a prescriptive one; dimensions are generic and require adaptation for specific domains.
IDE Startup Framework Gerdsri and Manotungvorapun (2021)	Map a pathway toward sustainable growth by connecting technical and business readiness.	MRL, CRL, BRL	Context-specific to startups; primarily focused on a commercialization pathway.
READINESS-Navigator Eljasik-Swoboda et al. (2019)	Adapt readiness assessment for AI/ML innovations where data is a key resource.	Replaces MRL with AIRL and DRL.	Highly specific to a technology type; not tailored for an application domain like security.
MDRL Framework van de Loo et al. (2022)	Tailored assessment for high-risk medical devices, integrating human factors.	Human RL concepts (usability, comfort), safety, clinical effectiveness.	Highly domain-specific; requires extensive clinical and regulatory expertise.

fundamentally different from the goal of assessing a specific technology's readiness for uptake, which is the focus of MultiRATE.

In summary, existing holistic frameworks provide valuable philosophical and methodological precedents. The clear evolution toward context- specific, multi-dimensional dashboards aligns with the approach taken by MultiRATE. By visualizing multiple readiness levels, these methods offer a more transparent and actionable alternative to opaque composite indices, allowing for the identification of specific weaknesses. This is a significant ad- vantage over simpler process-focused guides or singular RL scales. However, no existing framework provides the specific combination of harmonized dimensions required for the civil security domain. The state-of-the-art lacks a framework that concurrently and systematically evaluates TRL, IRL, MRL, CRL, SocRL, and, most critically, the specific requirements of SecRL and LPERL Adomaitis et al. (2024). This identified gap calls for a constructive research approach aimed at creating a novel solution. For this purpose, the Design Science Research Methodology (DSRM) provides a suitable structure for developing and evaluating a new artifact to address a specific problem Peffers et al. (2007). Unlike purely descriptive methods that analyse existing phenomena, DSRM offers a rigorous process for the design, implementation, and validation of a practical solution. Its iterative nature is particularly advantageous for a complex undertaking like the MultiRATE HRL, which requires harmonizing multiple, disparate readiness dimensions into a single, coherent framework validated by expert stakeholders. This methodological foundation ensures that the resulting artefact is not only theoretically sound but also demonstrably useful in its intended context.

Method

The methodological approach of the MultiRATE HRL assessment, first introduced in its white paper van der Lee et al. (2025), integrates seven distinct RL dimensions (TRL, SocRL, SecRL, LPERL, IRL, en-CRL, and MRL) to create a holistic evaluation. A key design principle is to maintain the integrity and unique characteristics of each RL scale while providing a holistic view of a technology's feasibility and progress. To achieve this with heterogeneous RL dimensions, some of which do not share the same number of levels, the MultiRATE HRL adopts a flexible harmonization strategy. This approach is conceptually similar to state-of-the-art holistic frameworks like the IDE Startup Framework Gerdsri and Manotungvorapun (2021), the ENISA CSIRT model European Union Agency for Cybersecurity (ENISA) (2019), and the C2M2 framework U.S. Department of Energy (2022), which harmonize the levels of different RL scales from a higher-level perspective. This contrasts with the more rigid, one-to-one level mapping found in models like the EU 4-Axis Framework Bruno et al. (2020) and BRLa Vik et al. (2021). The chosen methodology offers the advantage of accommodating diverse RL scales and allowing for the assessment of non-technical maturity improvements required to achieve a ready-to-market solution, even beyond the scope of TRL9.

Another key design principle is to consider two kinds of assessments: (1) a quick holistic RL assessment of an "element" (i.e., the product, system, or process under evaluation) to get a preliminary result, and (2) a full holistic RL assessment of the same element with more time to get a more detailed result. The full holistic assessment is intended to be conducted by a group of expert users that would answer the full list indicators related to their expertise. The result of this full assessment will be the most accurate and detailed that MultiRATE HRL can provide. On the other hand, the quick holistic assessment is intended to be conducted by only one user, not necessarily an expert in all the fields. In this case, the result will not be as accurate and detailed, but it will be quicker and simpler to answer by a non-expert. Therefore, in practice, the quick assessment modality could be seen as a preparation for a full assessment, while the full assessment modality is required for a formal assessment with more detailed insights on the obtained MultiRATE HRL and the more specific pending points towards a higher maturity of the element.

To measure the MultiRATE HRL of an element, the user must answer a series of indicators associated to each of the RL dimensions. In a full assessment, the indicators of TRL, SocRL, SecRL, IRL, en-CRL and MRL can be answered with five possible answers: "N/A" (Not applicable), "Nothing", "Partially", "Largely" and "Fully" implemented. If all indicators related to a level of the RL scale are answered with "Fully", the level is 100% achieved, if all are "Nothing", the level is 0% achieved, and the in-betweens are calculated proportionally. The "N/A" responses are ignored from the computation, but there is a limit of N/A responses per level to be able to compute the results (20%). In the quick assessment, as there are a few questions per level, N/A is not available as a possible answer. LPERL Adomaitis et al. (2024) is computed in a different way as explained in the following subsection, with "Yes"/"No" possible answers. Next, we will introduce more in detail the individual MultiRATE RL dimensions and then how they are combined for a holistic assessment.

MultiRATE readiness level dimensions

a) Technology Readiness Level (TRL)

The TRL assessment methodology developed within the scope of MultiRATE, is mainly based on the categories of indicators that were defined in previous attempts and builds on them, according to the further research which has been conducted within MultiRATE. Those indicators form the base, on the list of questions which apply for each TRL level. Under MultiRATE project, TRL further expanded the TRL assessment methodology enhancing the developed tool in order to further improve the quality of the assessments. To enrich the framework, an extensive literature review has been conducted, resulting in the extraction and inclusion of additional indicators while the indicators were further modified and tailored to fit the usage of the overall approach to the EU R&D projects. These indicators provide a more comprehensive and context-specific evaluation, ensuring that the framework captures relevant factors for assessing the system's readiness and usability.

The evaluation framework of the MultiRATE TRL assessment, comprises four distinct indicator categories which include all the identified indicators: 1) Technology Preparation & Requirements, 2) Documentation, 3) Operability & Continuity, and 4) Evaluation & Usability. These categories serve as key aspects for assessing the readiness and effectiveness of a system. Each RL is comprised by a set of indicators. Some indicative aspects of indicators per category include the following as indicated in Table 3.

b) Societal Readiness Level (SocRL)

The MultiRATE SocRL is used to assess the level of adaptation of an innovation to be successfully adopted by society. The use of the umbrella term 'innovation' in the case of the SocRL is a purposeful indication of the necessary focus it has for its assessment. Innovations include the use of a new piece of equipment, system, software, methodology, or procedure within a context it has not been used before. Innovations are based on the results of new technological developments, technology combinations, or other knowledge towards societal well-being, and should be developed alongside continuous stakeholder input to ensure they are suitable for their intended purpose and accepted within their context. The inclusion of a variety of different stakeholders in the research and innovation process forms a key component to validating readiness as part of the SocRL assessment.

Previous work has been carried out into societal readiness, with the most well-known scale coming from Innovation Fund Denmark Innovation Fund Denmark (2019). However, the existing works on societal readiness were fragmented and incomplete for the purposes of MultiRATE's proposed comprehensive assessment framework; additionally, past research tended to focus on the areas of energy, decarbonization, and sustainability Sprenkeling et al. (2022); Büscher et al. (2023), and therefore more work was needed in order to apply these societal considerations to the security domain, where they are just as, if not more, relevant than ever.

The MultiRATE SocRL includes measures such as the take-up and acceptance of an innovation by society. There are four categories of indicators that together form the criteria for the assessment: 1) Stakeholder Engagement, 2) Acceptance, 3) Societal Integration, and 4) Societal Good, presented in full in Table 4. These categories and the indicators associated with them are based on the work of past tools used to assess societal readiness in a variety of different ways Space53; New Horrizon; IsITethical. The SocRL features nine levels, ranging from the initial identification of the societal need, societal good, and associated readiness aspects of the innovation in question, all the way up to finally proving its benefit within

Table 3. **MultiRATE TRL indicator categories.**

Category	Indicative aspects of indicators included
Technology Preparation & Requirements	User requirements, system specifications, architecture, data flows, HW and SW requirements, software specifications
Documentation	Documentation of specifications, installation and operation guides, user guides
Operability & Continuity	Deployment, installation, operation, and maintenance
Evaluation & Usability	End user testing and evaluation, overall efficiency of the tool, end-user friendliness

Table 4. **MultiRATE SocRL indicator categories.**

Category	Indicative aspects of indicators included
Stakeholder Engagement	Engaging and involving a wide range of stakeholders and their considerations in the research and innovation process.
Acceptance	Taking into account the benefits, risks, societal concerns, and trust related to the innovation and involved practitioners through stakeholder engagement, especially with citizens.
Societal Integration	How the innovation fits into practices, place-based policy, cultures, and social trends, helping ease the integration of the innovation into everyday lives of the future.
Societal Good	The intentions, priorities, co-benefits, and consequences of the innovation, contributing to and promoting societal well-being.

society after launch on the market. The levels used in the MultiRATE assessment framework are adapted from those previously proposed for societal readiness Sprenkeling et al. (2022); Büscher et al. (2023).

The SocRL predicts the readiness of and helps prepare an innovation along its journey of adoption. The full assessment has a total of 50 indicators, however, a quick version of the SocRL assessment was also developed for MultiRATE that has only 14 indicators across all nine levels. The quick assessment works by using only a handful of the most crucial indicators across the different categories and levels. The result is a highly reduced assessment, but one that can still give an approximation of the user's potential SocRL without undertaking a full assessment.

c) Security Readiness Level (SecRL)

The MultiRATE SecRL scale allows assessing the degree of security of a given element and its assets in relation to its threat environment and the applied security measures as well as the security testing complexity. The SecRL is a scale for measuring the security of an innovation, product, or solution (a process or a technology) and its assets concerning its threat environment. Each level increase implies risk reduction, meaning reducing the likelihood and severity (e.g., damage) of the impact of security incidents by adjustments in design and introducing more or better countermeasures or security capabilities. Since there was no previous attempt for the SecRL that aligns the MultiRATE's purpose of evaluating and determining the security maturity of any kind of solution (in the field of civil security), it had to be built within the scope of MultiRATE. The methodology used was to harmonize the previously identified Security Maturity Model with international security standards such as ISO 15408. The basic framework and level structure are derived from the guidelines for using TRLs in ESA programs. It ranges from SecRL 1 (security considerations) as the lowest level to SecRL9 (Operational Security Validation) as the highest level. The total number of relevant indicators for the nine security levels has been streamlined to 41. There are eight different types of indicators, which provide valuable insights into various aspects of security readiness. Among these types, the largest one is the "Security Testing, Improvement, and Iteration" type, which encompasses most indicators ranging from SecRL 5 to SecRL 8. Although there was a possibility to further divide the "Security Testing, Improvement, and Iteration" type into more detailed subtypes such as "test development," "test conduction," and "test iteration," the decision was made to maintain good alignment with the other RLs in MultiRATE. This ensures consistency across the different readiness levels and facilitates comparison and analysis. The externalization of definitions, explanations, and examples helped to make the indicators shorter and more precise. Further details can be found in Adomaitis et al. (2024).

d) Legal, Privacy, and Ethics Readiness Level (LPERL)

The MultiRATE LPERL scale allows assessing the degree of alignment with European values and rights, provide guidance in ethics by design and promote responsible application of solutions. A key aspect is the identification-characterization-harmonization-control paradigm. The four-level structure of LPERL applies this paradigm to the domain of technology ethics, providing a systematic approach to identifying, characterizing, harmonizing, and taking control of ethical issues.

LPERL 1 encompasses the step of identifying potential ethical dilemmas, privacy concerns, and legal implications associated with the system. At LPERL 2, the relationships and trade-offs between various ethical issues are reflected. LPERL 3 shows operationalization and involves the integration of ethics considerations into the system design, a process often referred to as "ethics by design". Finally, LPERL 4 shows control mechanisms for accountability and the attainment of standard benchmarks and certifications, if applicable. This ERL structure combines anticipatory ethics with ethics by design and streamlines the management of emerging AI technologies.

To evaluate LPERL level, the tool includes more than 200 indicators grouped in blocks. In the area of security, the LPERL blocks include: 1) a basic technology ethics module for all use cases, 2) AI-specific block, 3) Law Enforcement block, 4) Personal data block. The number of indicators actually used during evaluation depends on the use case. Further details can be found in Adomaitis et al. (2024).

e) Integration Readiness Level (IRL)

The Integration Readiness Level (IRL) scale is a framework for determining the maturity and readiness of an element for integration into a larger system or environment. It provides a standardized method for assessing the readiness of technologies, software, or hardware for integration, assisting in the identification of potential risks and issues and promoting effective decision-making during the integration process by establishing clear benchmarks and criteria for assessing readiness. Furthermore, it allows stakeholders to track the status of integration efforts, prioritize activities, and allocate resources more efficiently reducing integration risks by encouraging early detection and resolution of difficulties, hence enhancing the overall success rate of integration initiatives.

The IRL framework consists of 34 indicators grouped into nine levels. Originally based on the Sauser and Forbes model, the IRL framework has been refined to provide a more systematic and progressive approach. This updated model guides end-users through the integration process, from initial identification to real-world applicability. The 9 level descriptions are presented in Table 5.

To this end, the IRL follows a structured progression via three key stages: (i) The definition and specification; (ii) the testing and validation and (iii) the deployment and optimization stage. In the first stage key elements are identified, objectives are set, and specifications are clearly defined to establish a solid integration framework. The second phase focuses on testing and validation to ensure successful integration in different context environments. In the last stage, the system is deployed in real-world conditions, monitored for stability, and continuously optimized to ensure long-term reliability and performance improvements.

Table 5. Description of the MultiRATE Integration Readiness Levels (IRL).

IRL level	Description
1. High-level concepts identified	Fundamental concepts and overarching principles relevant to the integration process have been identified and delineated. These involve defining high-level goals, outlining the overall architecture, identifying critical components, and establishing initial approaches to integration.
2. Basic requirement specifications defined	The essential functionalities, constraints, and criteria that the integrated solution must fulfil to meet its intended objectives are defined.
3. User requirements and integration tests defined	The user requirements that the integrated solution will meet are clear and a framework for the integration testing is defined.
4. Technology validated in laboratory environment	The functionality, performance, and feasibility of integrating the elements have been validated in a controlled laboratory environment.
5. Technology validated in relevant environment	The performance, functionality, and compatibility of the elements have been validated in an environment that closely resembles the conditions in which it will be deployed and used in real-world scenarios.
6. Technology validated End-to-end operations	The integrated elements were tested and validated across its entire operational workflow, from start to finish, under real-world conditions.
7. System prototype demonstrated in operational environment	A functional system prototype has been demonstrated in a operational environment with a tangible demonstration of its capabilities, performance, and suitability for real-world deployment.
8. System integration validated by its end-users	The integrated system of the element is tested with end-users in the operational environment and is then prepared for long-term maintenance.
9. System integration proven in operational environment	The system is deployed in a operational environment and the monitoring/maintenance procedures are in place.

In order to facilitate the users' assessments, a simplified version of the IRL framework has also been designed. This simplified scale retains the most representative indicators, allowing end-users to conduct assessments more efficiently maintaining the objectives of the original framework.

f) Enhanced Commercialization Readiness Level (en-CRL)

The MultiRATE en-CRL scale enhances previous CRL models Paun (2012); Australian Renewable Energy Agency (2014); Vik et al. (2021); Gerdsri and Manotungvorapun (2021) to align with the Holistic Innovation Management Methodology (HIM) Sofou (2017). Following the HIM, the scale builds on project "Results" -as these are defined in the EU Grant Agreement signed between the European Commission and the consortium of an EU-funded project (i.e., any output of the action, tangible or tangible, whether or not it can be protected)- and aims to improve the commercialization strategy for the products embodying these "Results".

The en-CRL scale maintains 9 levels suggested in previous work, but differs substantially in that it introduces a list of different indicators for each Level. It allows assessing the maturity of an element to be launched, taking under consideration: the market & competition analysis relative to the element, its IP protection and freedom to operate, the team's expertise, certifications & adherence to standards, contracts with suppliers, exploitation agreements, customer support plans, as well as marketing & risk mitigation plans. Its goal is to support an exploitation team in assessing their product's readiness for the market, and enrich the action plan to improve the product's commercialization strategy and innovation adoption. This is in line with the combined strategy for IP management, exploitation, dissemination and data management of project "Results", throughout their lifecycle, as proposed in Pestana and Sofou (2024).

Six indicator categories (IP Management, Market Potential and Competitive Landscape, Team and Consortium Expertise, Solution Definition/Design/Development, Exploitation Plan, Manufacturing/Supply Chain) are examined in a 9-step assessment process, and the indicators serve as guidelines to achieve the goal. The full version of en-CRL comprises of 9 Levels, 6 categories and 35 indicators. A version for quick evaluation is also available, with 18 indicators covering all 6 categories and 9 levels.

g) Manufacturing Readiness Level (MRL)

The MultiRATE MRL scale allows assessing the maturity of a manufacturing process throughout its conception, proof of concept, realization in a laboratory scale and demonstration in a pilot production line or a low-rate initial production United States Department of Defense (2025). MRL is used to provide decision makers with a common understanding of the relative maturity and attendant risks associated with manufacturing technologies, products, and processes being considered. It aims to define the current level of manufacturing maturity, to identify maturity shortfalls and associated costs, and to provide the basis for manufacturing risk management. This scale is based on prior MRL models Wheeler and Ulsh (2009); Schumacher et al. (2016); Basu and Ghosh (2017). The original indicators served as a baseline and were subsequently refined, adapted, and expanded to address the specific context and aims of EU Research and Development Security Projects. These indicators provide a more comprehensive and context-specific evaluation, ensuring that the framework captures relevant factors for assessing the system's manufacturing readiness. The evaluation framework of the MultiRATE MRL assessment, includes 67 total indicators, consists of 9 levels of Manufacturing Maturity, comprises 8 distinct indicator categories namely: Manufacturing Process, Supply Chain Readiness, Production Capacity, Quality Control and Assurance, Manufacturing equipment and machinery, Cost and Efficiency, Training and Workforce, Regulatory and Compliance.

MultiRATE holistic readiness level assessment

The holistic RL assessment workflow consists of three main phases: (1) Initialization, (2) HRL calculation and (3) HRL results analysis. Next, we will describe each of these phases more in detail.

a) Initialization

During the initialization phase, the user(s) of the HRL assessment system need to select some values from a series of concepts shown in Table 6 to configure the system for a specific assessment.

These concepts include the security field area to which the project belongs, whether the element involves human subjects, and if it includes AI. To aid in understanding the context of the users who will perform the assessment, there are concepts related to the specific use case, user type, purpose of the assessment, and whether it is a quick or full assessment. Additionally, the final concepts assist in refining the starting point of the RL scales or excluding them from the

Table 6. Concepts in the initialization form.

Concept name	Options
Security area	Border management, Disaster Resilient Societies, Fighting Crime and Terrorism, Digital Security, Infrastructure Resilience, Strengthened Security Research and Innovation, Other
Nature of the element	Hardware, Software, Hardware&software, Methodology/Procedure, Methodology/Procedure&Hardware, Methodology/Procedure&Software, Methodology/Procedure&Hardware&Software
Involves human subjects	Yes/No
Includes AI	Yes/No
Use case	Tech development orientation, Innovation uptake (sup- ply side), Innovation uptake (demand side), Standardization policy support, R&I programming and management support
User type	LEA (Law Enforcement Agency), Other first responder, Critical entity, Technology supplier, Other
Purpose	Self-assessment, Assessment by another company, Assessment by a 3rd party for certification
Quick assessment	Yes/No
Starting xRL	Excluded/1-9/Complete
Exclude LPERL	Yes/No

assessment. In the case of LPERL, there is no starting point as previously explained, so it only has the option of being excluded or not.

b) HRL calculation

After the initialization, users can access relevant indicators of the RL dimensions to assess an element's holistic maturity. As explained at the beginning of this section, by responding to these indicators, the degree of accomplishment for each level is calculated as a percentage. A level is considered "Fully Achieved" if the percentage is above 80%, "Partially achieved" if 60-80% and "Not Achieved" if below that. There are also some additional rules to be considered during the HRL assessment. If a level is partially achieved, the next level in that dimensions can be assessed even if it is not accomplished. Another rule is that if a level is partially achieved, the following one can be fully achieved but the next one cannot be assessed until the previous partially achieved levels grow to fully achieved.

Thus, the user can visualize the results with a multi-dimensional RL dashboard in a similar way to other state-of-the-art holistic RL frameworks. However, our approach also integrates the RL dimensions into four holistic RLs that numerically represent the overall RL during the development of an element until it is ready for the market: HRL1—Solution concept, HRL2—Solution prototype, HRL3—Functional solution and HRL4—Ready- to-market solution. These holistic RLs take the well-established TRL scale as the main reference for the alignment of all RL dimensions into the four holistic RLs. TRL3 "Experimental proof of concept" is aligned with HRL1, TRL6 "Technology demonstrated in relevant environment(s)" is aligned with HRL2, and TRL9 "Actual solution proven in its operational environment" is aligned with HRL3. Beyond TRL9, dimensions that require additional effort for HRL4 include: SocRL7-9, SecRL9, en-CRL8-9, and MRL9. IRL is fully aligned with TRL, while LPERL's evaluation occurs at each HRL transition, ranging from levels 1 to 4. Table 7 shows this alignment more in detail.

Each HRL degree of accomplishment is calculated as the average of the aligned levels and that of LPERL. Therefore, HRL1 computes the average of TRL1-3, SocRL1-3, SecRL1-3, IRL1-3, en-CRL1-3, MRL1-3 and LPERL1-4, HRL2 the average of TRL4-6, SocRL4-5, SecRL4-6, IRL4-6, en-CRL4-6, MRL4-6 and LPERL1-4, HRL3 the average of TRL7-9, SocRL6, SecRL7-8, IRL4-6, en-CRL7-9, MRL7-8 and LPERL1-4, and finally HRL4 the average of TRL9, SocRL7-9, SecRL9, IRL9, en-CRL8-9, MRL9 and LPERL1-4.

Table 7. Alignment among MultiRATE RL dimensions for HRL computation.

HRL	LPERL	SocRL	CRL	TRL	IRL	SecRL	MRL
HRL 4 Ready-to-market solution	1-4	7-9	8-9	9	9	9	9
HRL 3 Functional solution	1-4	6	7	7-9	7-9	7-8	7-8
HRL 2 Solution prototype	1-4	4-5	4-6	4-6	4-6	4-6	4-6
HRL 1 Solution concept	1-4	1-3	1-3	1-3	1-3	1-3	1-3

c) HRL results analysis

To better understand the obtained HRL results, we recommend using two kinds of graphs: (1) A spider graph including reference RL dimension distributions per holistic level (Figure 1), and (2) bar graphs showing the degrees of accomplishment (Figure 2). These graphs allow spotting easily the weak points in the maturity of the element being assessed. More specifically, the spider graph shows the levels achieved (partially or fully) in each dimension compared to the expected achievements for each holistic level, making it easier to identify dimensions requiring further improvement to increase holistic maturity. On the other hand, the bar graphs provide a detailed visualization of the degrees of accomplishment across all levels, regardless of whether they have been fully achieved, allowing users to concentrate on specific dimension levels needing enhancement. Furthermore, by identifying these weak points against the references, a simple program can be developed to automatically provide feedback to the user(s), guiding them towards the next steps in improving the holistic maturity of the element being evaluated.

d) Readiness Level Investment Forecasting

One important objective of the MultiRATE project's forecasting module was to develop a robust and objective method for estimating the necessary investment for the development of a specific element. Recognizing the inherent variability and lack of balance in monetary investment across different regions, such as within the European Union, we opted to use effort allocated in EU-funded projects, measured in person-months (PMs), as a more stable and representative metric. This approach allows to address the fundamental question: "How much effort, in person-months, is required for an element to advance from one specific Technology Readiness Level (TRL) to another?"

To enable this estimation, the first step is to define an element through meaningful and precisely measurable features. Through extensive internal discussions within the MultiRATE project consortium, it is established that these features must be quantifiable, consistent, and verifiable to build a reliable dataset for the FM system. The discussion focused on data points that have undergone rigorous validation by the European Commission (EC), ensuring their accuracy as part of either funded or completed projects. The final set of features selected for our analysis includes:

- **Project Duration:** The total time span of the project in which the element was developed, and the duration of the element development.
- **Technology Readiness Levels (TRLs):** Both the initial and final TRLs of the element, indicating its developmental stage.
- **Person-Months (PMs):** The total effort expended on the project, and specifically on the element's development, measured in person- months.
- **Number of Participants:** The total number of organizations or individuals involved in the project and specifically in the element development.

This careful selection process ensured utility of the MultiRATE FM dataset, forming the bedrock for the forecasting methodology.

A significant challenge in developing this forecasting module was to effectively capture the intrinsic relationships among disparate features and individual data samples. The nature of the gathered data, which are unstructured, presented an ideal scenario for the application of graph-based method. The idea is that by treating the data as graphs, these inherent connections could be more powerfully exploited.

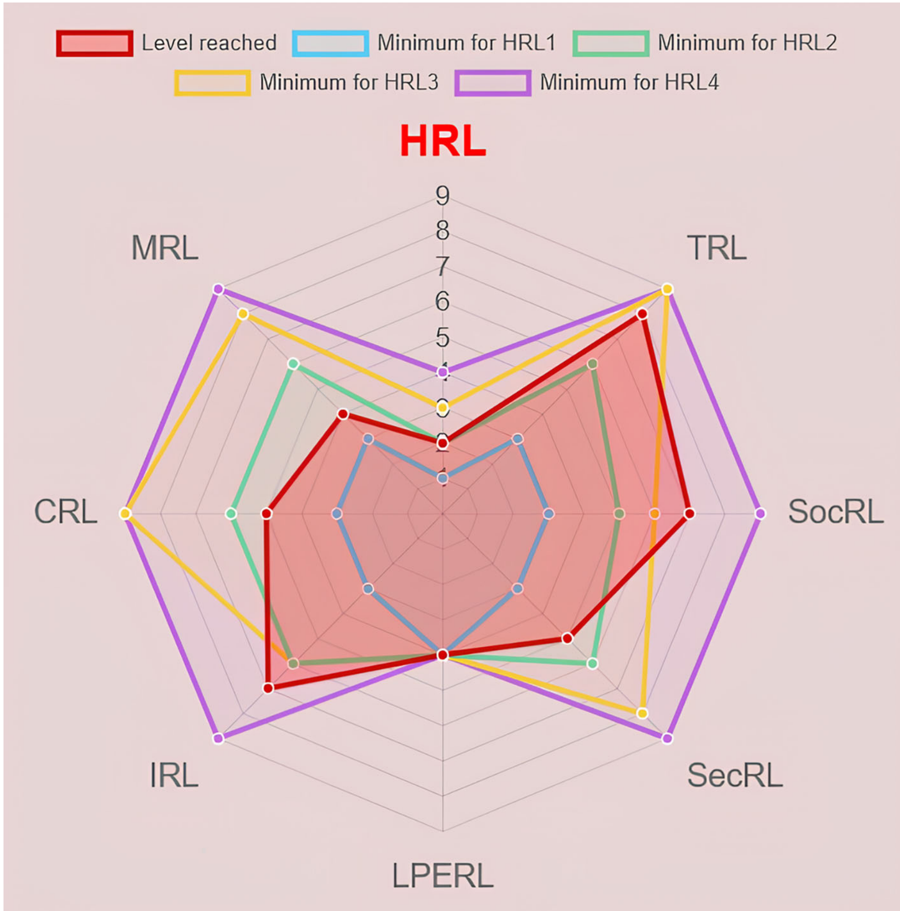

Figure 1. **An example of assessment results visualized with a spider graph with respect to levels expected for each HRL.**

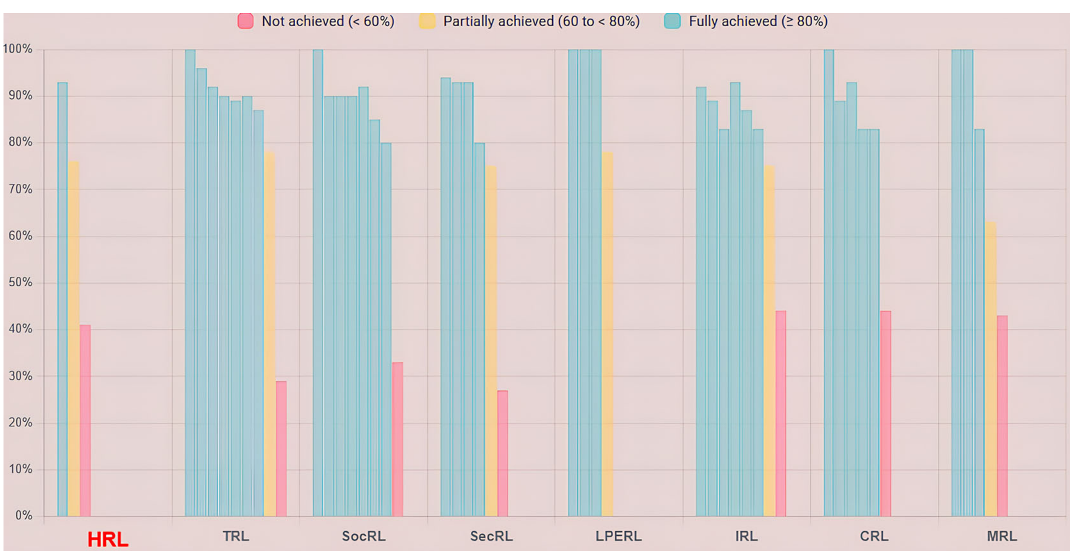

Figure 2. **An example of assessment results visualized with bar graphs showing degrees of accomplishment.**

Consequently, an end-to-end graph-based method was adopted as the foundation of the forecasting module. Initially, the unstructured raw data is transformed into a fully connected graph. Following this initial construction, the forecasting module (FM) then dynamically learns and optimises the most effective graph structure with respect to the ultimate task of node classification. This adaptive approach allows the system to identify and prioritize the most salient relationships within the data, leading to more accurate and insightful predictions Marthoglou et al. (2024). This methodology moves be- yond simple correlation, enabling a deeper understanding of how different factors interdependently influence development effort.

To facilitate user interaction with the forecasting module and to present the results in an intuitive manner, a custom 3D graphical user interface (GUI) was developed. This GUI is seamlessly integrated into the MultiRATE project's broader visual analytics dashboard, providing a unified and comprehensive user experience.

The GUI empowers users to input the specific features of the element under inspection and submit them to the forecasting service. Upon submission, the forecasting module instantly provides the estimated effort. Crucially, the inserted element is then visually represented within the GUI as a 3D object, offering a multi-dimensional perspective on the forecast. This 3D representation dynamically displays key information, including:

- **Duration Information:** Numerical values and relative proportions for both the overall project and the specific element.

- **Person-Months Information:** Numerical values and relative pro- portions for both the overall project and the specific element.

- **TRL Information:** The TRLs of the project are represented both spatially (through the object's dimensions) and visually (through a colour scale).

A clear legend on the right side of the interface explains the colour coding, enhancing interpretability. For detailed inspection, users can hover over the 3D object to reveal pop-up boxes containing precise data, and all element information is also accessible in an organized list at the bottom of the page (Figure 3). Furthermore, the web application incorporates a valuable comparison feature, allowing users to juxtapose two different elements and analyse their estimated efforts side-by-side, fostering a more comprehensive understanding of development requirements (Figure 4).

Evaluation with external network of experts

The presented methodology and all its components (i.e., the artefacts) have been evaluated by the MultiRATE project's stakeholder network; a diverse group of experts and organizations, including research projects and supporting entities, that represents the EU's security Research and Innovation (R&I) landscape. To structure the network, members were categorized by type and by their level of engagement: "hard engagement" involved active collaboration under legal agreements like a Non-Disclosure Agreement (NDA) or Memorandum of Understanding (MoU), while "soft engagement" entailed occasional feedback through surveys or events without such commitments. To ensure a representative sample, the Research & Innovation (R&I) projects within the network were further classified by thematic security area. These areas include Border Management (BM), Disaster Resilient Societies (DRS), Fighting Crime and Terrorism (FCT), Digital Security (DS), and Resilient Infrastructure (INFRA). Table 8 and Table 9 summarize the number of members and their distribution based on these criteria.

Validation plan

To conduct the design and validation activities, Design Science Research Methodology (DSRM) was used, to formally implement an objective, utility based, and end-user centric approach, and conduct the activities in iterative cycles to elicit frequent feedback. DSRM incorporates principles, practices, and process models which are adequate to conduct design science research in applied research disciplines, whose cultures value incrementally effective solutions Hevner and Chatterjee (2010). The design science paradigm seeks to create and evaluate "what is effective" in the problem space Hevner et al. (2004). For the final validation cycle, a System Usability Scale questionnaire was used, tailored to the needs of MultiRATE and mapped to DSRM.

Four design and validation cycles were scheduled to allow for frequent synchronization of insights and lessons learned. Within each cycle, regular meetings were conducted to further synchronize development, validation, and network building activities.

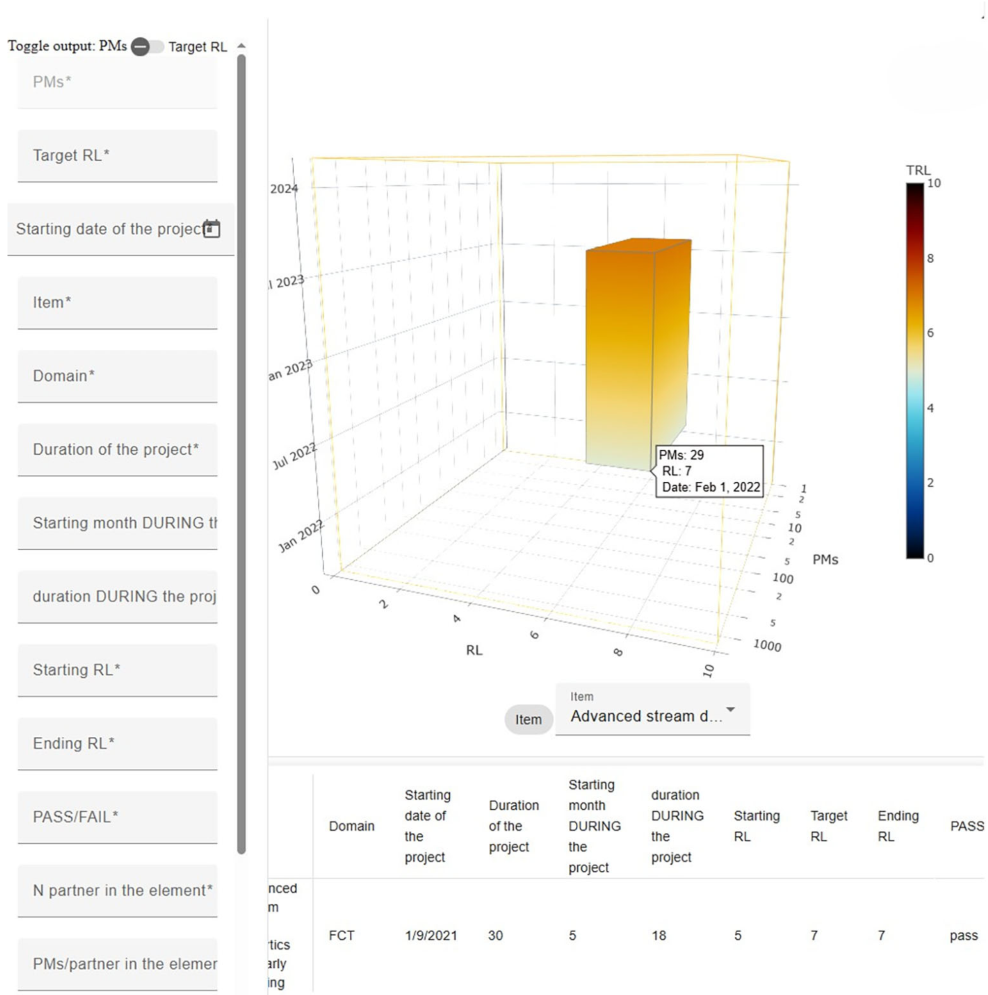

Figure 3. **An example of showing one element with input fields in the left sidebar.**

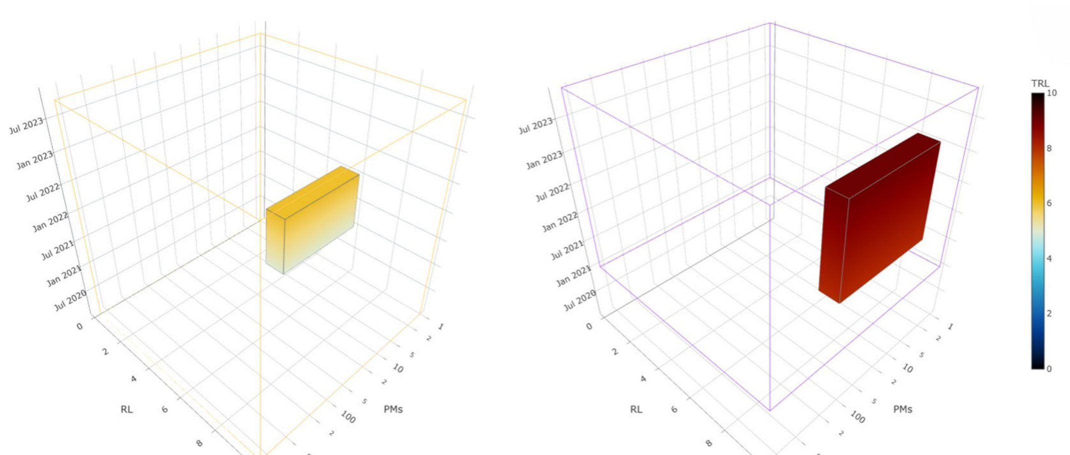

Figure 4. **An example of elements comparison.**

Table 8. MultiRATE stakeholder network summary.

Category	Identified	Hard	Soft	Total	Eng. rate	Weight
Security R&I projects	87	17	16	33	38%	60%
Supporting entities	15	3	3	6	40%	11%
EC and agencies	4	0	2	2	50%	4%
Other entities and experts	32	5	9	14	44%	25%
Total	**138**	**25**	**30**	**55**	**40%**	**100%**

Table 9. R&I projects engaged.

Area	Identified	Hard	Soft	Total	%
BM	14	2	3	5	15%
DRS	21	3	2	5	15%
FCT	25	10	5	15	45%
DS/CS	18	1	2	3	9%
INFRA	6	1	1	2	6%
Others	3	0	3	3	9%
Total	**87**	**17**	**16**	**33**	**100%**

The evaluation activities were performed according to the following procedures:

- **Data collection:** A common DSRM template was used to collect data for each MultiRATE artifacts, containing data fields for use cases, artifacts, system dimensions, evaluation criteria, objectives, formal ratings, and informal evaluators' feedback.

- **Data analysis and reporting:** Each artefact owner collected feedback received during the evaluation sessions; feedback was then shared with other artefact owners, as well as analysed and discussed during regular meetings; additionally, formal reporting was provided through project deliverables.

- **Implementation:** Based on feedback received, as well as the development backlog, each artefact owner selected the set of features to be implemented for the following development iteration.

The DSRM process model adopted was based on the model developed by Peffers et al. (2007), as shown in the diagram of Figure 5.

Validation results

In the fourth evaluation cycle, external evaluators were contacted to test the HRL web-based calculator, with all RLs now fully integrated as a part of the methodology. Overall, based on the feedback received, the HRL calculator shows potential as a useful tool but requires significant enhancements across multiple domains. A primary and widespread concern is its understandability; evaluators frequently reported that concepts were complex, wording was confusing, and results, particularly graphs, were difficult to interpret without further explanation. Users requested clearer HRL level explanations, improved guidance, and a more intuitive UI/UX design. Efficacy is another critical area needing attention, with specific feedback highlighting potentially flawed HRL calculations when Industrial or Manufacturing Readiness Levels (IRL/MRL) are not applicable or are dropped. The tool's current primary focus on "products" rather than processes, and the absence of key assessment components such as the usability of a product by a user (Human Readiness Level) or items like the availability of training curricula, were also noted as limitations to achieving its purpose. Regarding its practical utility for users, issues such as the inability to change initial parameters once set and cumbersome UI elements like the lack of an "expand all" feature for questions were raised. For the tool to achieve better organizational fit and utility, suggestions included making it more generic beyond specific EU-funded security research actions, ensuring it encompasses a broader range of project types and funding areas, and providing clarity on its value proposition, data handling, and integration into organizational practices like proposals. Finally, a need for a greater level of detail through more sufficient contextual help and guidance within the tool was also explicitly requested by users.

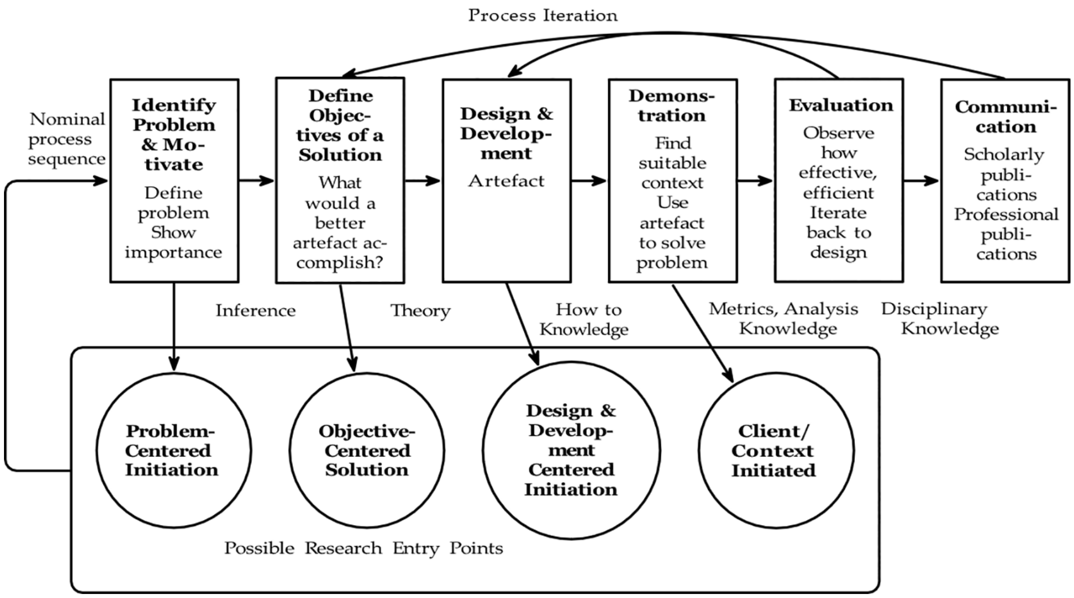

Figure 5. **DSRM process model Peffers et al. (2007).**

Throughout the final evaluation cycle, the web-based calculator has been modified in response to the feedback received. More specifically, a couple of updates have been applied starting from additional explanations that have been added to the indicators that contained keywords that weren't clear enough. Secondly, the wording in some explanations has been improved for use beyond EU projects or products. Then, the menu for selecting different assessments has been enhanced by including additional details such as the project name, element name, and whether it is a quick or full assessment. This improvement allows easier navigation between assessments and enables users to compare, for instance, the quick and full assessments of the same element more effectively. Additionally, the user manual has been improved, adding a step-by-step guide with a practical example showing the differences between the quick and the full assessments of an element. Last but not least, graphs have been improved with more explanations to better understand their meaning. Besides, automated feedback for improving the holistic RL of the assessed element has been added.

During the fourth evaluation cycle the System Usability Scale (SUS) questionnaire, tailored to the needs of MultiRATE, was used to simplify the evaluations and the method to receive feedback from the external participants. SUS is a well-established questionnaire which uses 10 questions, and the responses are based on the Likert scale with 5 response options. Except for the ten questions of SUS, we added one question per RL (including HRL) to measure the expectation of the evaluator compared to the results of the assessment for each RL. Six more questions were added, focused on the HRL from which two are open questions. EU Survey was used to create the questionnaire, and it was distributed after each evaluation of element(s) using HRL. Furthermore, MultiRATE consortium created a mapping between the SUS (Table 10) based evaluation questionnaire and the DSRM methodology (Table 11). The questions as well as the number of replies are depicted. For coherency purposes, the questions are presented below from i to x.

i) I think that I would like to use this system frequently.

ii) I found the system unnecessarily complex.

iii) I find the system easy to use.

iv) I think that I would need the support of a technical person to be able to use this system.

v) I found the various functions in this system were well integrated.

vi) I thought there was too much inconsistency in this system.

vii) I would imagine that most people would learn to use this system very quickly.

Table 10. SUS (System Usability Scale) evaluation results. The table displays response counts for ten questions (i-x).

Response type	i	ii	iii	iv	v	vi	vii	viii	ix	x
Strongly Agree	12	1	9	3	11	1	17	0	6	1
Agree	14	2	20	0	18	1	8	2	19	2
Somewhat Agree	7	4	4	2	5	2	8	5	7	4
Somewhat Disagree	2	3	2	5	2	2	2	1	4	5
Disagree	2	17	2	8	0	15	0	10	1	16
Strongly Disagree	0	6	0	11	0	8	0	9	0	5
Blanks	**0**	4	0	8	1	8	2	10	0	4
Total Responses	**37**	**37**	**37**	**37**	**37**	**37**	**37**	**37**	**37**	**37**
Positive Responses	**89.2%**	**78.8%**	**89.2%**	**82.8%**	**94.4%**	**86.2%**	**94.3%**	**74.1%**	**86.5%**	**78.8%**

Table 11. MultiRATE HRL evaluation criteria and objectives based on DSRM.

System dimensions	Evaluation criteria/ Subcriteria	Objectives
Goal	Efficacy	The degree to which the HRL has achieved its purpose.
Environment	Consistency with people/Utility	While conducting the maturity evaluation of a project element, the HRL tool/method is useful for assessing it holistically.
Environment	Consistency with people/ Understandability	While conducting the maturity evaluation of a project element, the HRL tool/method enables easy understanding of the intermediate achievements needed in order to reach the desired final achievement and comply with the project contractual obligations.
Environment	Consistency with organization/ Utility	The HRL is useful for the services offered by the organization, it provides evidence on whether the element is on good stage.
Environment	Consistency with organization/ Fit with organization	The HRL can be easily fit in the organization practices.
Structure	Level of detail	The HRL provides a sufficient level of detail needed for its goal on an executive summary level.

viii) I found the system very cumbersome to use.

ix) I felt very confident using the system.

x) I needed to learn a lot of things before I could get going with this system.

Regarding the individual RLs, i.e. TRL, SocRL, SecRL, LPERL, IRL, en-CRL, and MRL, evaluators were asked to what degree the RL assessment results matched their expectations. The results demonstrated that MultiRATE presents a high overall average of more than 80% accuracy. Additionally, regarding the evaluation on the FM, as presented in Table 12,

Table 12. Evaluation results for the forecasting module.

Question	Answers
Was the procedure clear enough for the user to follow and were the instructions adequate to understand the usage?	Yes: 5/7 Needs more tooltips/info: 1/7 Not exactly: 1/7
How easy was the tool to use? (Scale 1-7)	14.3% (5)|71.4% (6)|14.3% (7)
Environment Consistency with people/Utility (Scale 1-7)	28.6% (6)|71.4% (7)
What is the Goal of the tool - About Efficacy	57.1% LA|42.9% FA
Environment Consistency with Organization/Utility	42.9% LA|57.1% FA
Structure - Level of detail	71.4% LA|28.6% FA
Activity - Performance (Scale 1-7)	57.1% (6)|42.9% (7)

all 7 answers are positive, since in all answers evaluate the goals as Largely or Fully Achieved (LA and FA respectively), and the other questions are rated highly on a 1-7 Likert scale (1 answer 5/7, and all other answers 6 and above).

Conclusion

The traditional TRL scale does not fully address the complexities associated with security innovation. This paper introduced the MultiRATE Holistic RL framework as a direct response to this challenge, providing a validated, multi-dimensional approach to maturity assessment. By harmonizing seven critical RL dimensions our framework moves beyond a narrow technical focus to offer a truly holistic view.

Our main contributions are twofold. First, we developed a unified methodology that effectively integrates various readiness scales while preserving their distinct characteristics. Second, we implemented this methodology in the publicly accessible HRL calculator, a practical tool that provides not only a comprehensive assessment dashboard but also a novel investment forecasting module to guide resource allocation.

The validation of the HRL framework through the Design Science Research Methodology confirms its utility and feasibility for the civil security domain. Ultimately, MultiRATE provides a common language for researchers, end-users, and funding bodies, helping to de-risk the innovation process and bridge the “Valley of Death.” This work serves as a model for developing similar holistic assessments in other complex, high-stakes fields, championing a more responsible and effective pathway for technological transition. Future work will focus on adapting the framework for new domains, enhancing it with additional dimensions such as a Human Readiness Level, and conducting longitudinal studies to confirm its long-term impact.

Ethics and consent

Ethical approval for this study was obtained from the [MultiMoDal Data Fusion and Analytics Group ethics and legal team/Center for Research and Technology Hellas (CERTH)/Information Technologies Institute (ITI)] (Approval No.: A/A #2 14.01.2025). Written informed consent was obtained from all participants prior to their participation.

Data availability

No specific data associated with this article.

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Open Peer Review

Current Peer Review Status: ? ?

Version 1

Reviewer Report 07 April 2026

https://doi.org/10.21956/openreseurope.24564.r71524

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The manuscript develops what is, at its core, an attempt to resolve a long-standing problem in innovation assessment: the inadequacy of the traditional Technology Readiness Level (TRL) scale for complex, high-stakes domains like civil security. The authors argue that TRL's "narrow technical focus" fails to capture the broader ecosystem in which technologies operate, particularly non-technical dimensions such as societal acceptance, legal compliance, integration, and commercialization . In response, they construct the MultiRATE Holistic Readiness Level (HRL) framework, which integrates seven distinct readiness dimensions—TRL, SocRL, SecRL, LPERL, IRL, en-CRL, and MRL—into a unified assessment system. The framework is operationalized through a web-based calculator, supported by a structured indicator system and an investment forecasting module that estimates development effort using project-level data such as person-months and TRL progression . Methodologically, the authors rely on Design Science Research Methodology (DSRM) to iteratively design, implement, and validate the framework through expert engagement, producing what they present as a practical, policy-relevant tool that can "provide a common language" and help bridge the so-called "Valley of Death" in innovation systems .

What I find compelling in this approach is the authors' explicit recognition of the fragmentation problem in the readiness-level literature. Their description of a "Tower of Babel" of competing RL frameworks captures a real issue in the field, where multiple dimensions exist but lack integration . The move toward a dashboard-style, multi-dimensional framework is therefore well justified and aligns with broader trends in innovation systems thinking. However, precisely because the paper positions itself as a corrective to earlier conceptual and methodological limitations, I think it needs to be more explicit about the extent to which it actually escapes those same problems.

One point where I struggled conceptually is the treatment of aggregation. The authors explicitly acknowledge that "the mathematical validity of combining ordinal scores" has been widely critiqued and can produce a "false sense of precision" . This is an important admission. Yet later, the framework operationalizes the Holistic Readiness Level by calculating each HRL as "the average of the aligned levels" across dimensions . The way I see it, this averaging procedure appears to reproduce the very issue the paper initially problematizes—namely, treating heterogeneous and partially ordinal constructs as if they were commensurable on a single numerical scale. I would encourage the authors to clarify whether they see this as a justified simplification for usability, or whether there is a deeper methodological distinction they intend to draw between their approach and earlier composite indices. As stands, the work could use a concrete theorization of the move from critique to implementation.

A related issue concerns the implicit symmetry across dimensions. The framework structures HRL as an average across TRL, SocRL, SecRL, LPERL, IRL, en-CRL, and MRL, thus appears to assume that these dimensions contribute equally to overall readiness. Yet the paper itself emphasizes that these dimensions differ not only in content but in epistemological status—some are evidence-based and technical, while others are qualitative and context-dependent. The authors note, for example, that societal and commercial readiness "require significant qualitative analysis that can be difficult to standardize" . If this is the case, then equal aggregation raises questions about whether the framework is flattening meaningful differences between dimensions. I think the paper would benefit from explicitly addressing whether weighting is fixed by design or context-dependent, especially in a domain like civil security where ethical or legal considerations may outweigh purely technical maturity.

I am also enthused to ask how the framework handles variation across types of technologies and use cases. The authors state that the framework is designed to evaluate "products, systems, or processes developed in civil security R&I projects" , which is an extremely broad category. However, they did not fully unpack the implications of this breadth. Especially since technologies in this domain can range from low-risk administrative tools like say, bookkeeping software, to highly sensitive systems like predictive policing or surveillance platforms, and as a result, societal and legal dimensions becomes, not just additional factors but potentially dominant constraints. So I think the standardized structure of the framework forces a one-size-fits-all approach, especially since the paper does not fully address whether or how the relative importance of dimensions shifts across contexts. Even a short reflection on this would strengthen the applicability of the model.

On the validation side, I think the use of DSRM and expert feedback is appropriate for a design-oriented contribution, and the iterative structure is clearly described. At the same time, I think the paper could be more precise in how it characterizes its validation claims. For example, the results state that the framework achieves "more than 80% accuracy" based on evaluator feedback . This suggests to me that the "accuracy" reflects alignment with expert expectations rather than an external benchmark. That is not a weakness in itself—indeed, it is typical for this kind of research—but I would encourage the authors to frame it more explicitly as expectation-based or perceptual validation. Doing so would prevent readers from interpreting this as predictive or empirical accuracy in a stricter sense.

Finally, I think one of the most interesting tensions in the paper lies in the trade-off between usability and rigor. The authors deliberately introduce a "quick assessment" mode that "is intended to be conducted by only one user, not necessarily an expert in all the fields" . This is clearly motivated by practical considerations and enhances accessibility, however, it also throws questions about reliability into the frame, especially for dimensions such as legal, ethical, or security readiness that typically require specialized expertise. Note that the authors briefly acknowledge that this mode is "not as accurate and detailed," so I think the implications of this trade-off could be more fully explored, particularly in terms of how results from quick assessments should be interpreted or used in decision-making contexts.

Overall, this is a conceptually ambitious and practically relevant framework that addresses a real gap in readiness assessment for complex technologies. However, the manuscript requires major revision to strengthen its methodological coherence and conceptual clarity--It should more directly address the implications of aggregation across heterogeneous dimensions, justify or refine its equal-weighting logic, clarify the scope of applicability across different technology types, and more precisely frame the limits of its validation strategy. With these revisions, the paper would make a strong and credible contribution to the literature.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Global political economy, technology governance, and the study of digital and AI-enabled surveillance systems, particularly in the context of developing countries. I interrogate the adoption, evaluation, and governance of complex technologies across different institutional and political environments.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 17 March 2026

https://doi.org/10.21956/openreseurope.24564.r70294

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The manuscript titled "The MultiRATE Holistic Readiness Level framework for civil security technologies" intends to address the limitations of the traditional Technology Readiness Level (TRL) scale for complex civil security innovations by introducing a comprehensive, multi-dimensional Holistic Readiness Level (HRL) framework that integrates seven RL dimensions tailored to the security sector, including an investment forecasting module. This work aligns well with Open Research Europe's emphasis on open, reproducible research outputs with practical utility, such as the publicly accessible HRL web calculator, and it fits the platform's flexible article guidelines for research articles. I recommend major revision: the framework is innovative and the validation process is sound, but structural reorganization, expanded contextualization, and clearer methodological details are needed to fully meet the platform's standards for transparency and completeness.
The abstract follows a clear structure: it sets the context (TRL limitations and the "Valley of Death" in security tech assessment), states the objective (to introduce the MultiRATE HRL framework), outlines the methods (EU-funded project development, seven RL dimensions, expert validation via Design Science Research Methodology), reports key results (unified assessment with cost forecasting, positive validation), and concludes with implications (common language to de-risk innovation). It is concise and should encourage downloads by highlighting the free online tool. To refine further, the authors could trim a few adjectives (e.g., "significant problem") and ensure all terms like "MultiRATE HRL" are immediately self-explanatory.
The introduction clearly articulates the research problem: TRL's narrow technical focus fails to capture non-technical risks (integration, societal, legal, commercial) critical for civil security tech deployment, leading to fragmented assessments and the "Valley of Death." It reviews key RL extensions (e.g., IRL, MRL, SocRL) and their "Tower of Babel" challenges, motivating the need for a harmonized, sector-specific holistic framework. However, the section feels short and could be strengthened by expanding to 60–70 references overall (current count appears lower), adding more on civil security specifics (e.g., EU funding contexts like Horizon Europe) and explicitly stating the contributions in a dedicated paragraph.
The manuscript largely follows acceptable academic methods for framework development and validation. It employs Design Science Research Methodology (DSRM) within the EU MultiRATE project, adapting seven RL scales (TRL, SocRL, SecRL, LPERL, IRL, en-CRL, MRL) to security, integrating them into a dashboard with investment forecasting, and validating via structured expert questionnaires (positive ratings, e.g., mostly "Largely" or "Fully Achieved"). This is rigorous for an applied, design-oriented paper. However, the methods section dives into components without a brief general overview (e.g., "This study developed and validated a holistic framework using DSRM through iterative design, adaptation, integration, and expert evaluation"). It also lacks explicit justification for DSRM over alternatives (e.g., why not agile prototyping or Delphi method) and does not specify software used for analysis (e.g., for questionnaire scoring, web tool development—name and version). The authors should add these for full reproducibility.
The results present the framework's components, the HRL calculator (with link), and validation outcomes (e.g., high Likert scores, goal achievement ratings), supported by tables comparing RLs and expert feedback. These are clear and demonstrate feasibility. However, the manuscript lacks a distinct Discussion section, blending interpretation into Results and Conclusions, contrary to standard research article structure (Introduction, Materials and Methods, Results, Discussion, Conclusions). The authors must insert a Discussion to compare findings with prior holistic

frameworks (e.g., how MultiRATE improves on DoD SRL's ordinal issues or EU 4-Axis's omissions, per Table 1/2), highlighting unique attributes like security-specific RLs and cost forecasting.
The Conclusions summarize contributions (unified calculator, sector adaptations, validation) and implications (de-risking innovation for funders/users), with a nod to future work (e.g., other domains). To strengthen, it should explicitly list main limitations (e.g., validation sample size, security sector focus limiting generalizability, reliance on expert self-reports) and elaborate on policy/practical implications, such as EU R&I program integration, procurement guidance for LEAs, or startup investment roadmaps.
For the plagiarism I used the Turnitin software and found a similarity score of 12% which equally means >4% text in common with one source, >3% text in common with one source, >1% text in common with 2 different sources and <1% text in common with 27 different sources. The similarity score of 12% is good for me.
Furthermore, Turnitin software found that "this submission has been generated by AI" for 25% (Likely AI-generated text from a large-language model 25% and Likely AI-generated text that was likely revised using an AI-paraphrase tool or word spinner 0%). I do not know what about text generated by AI. Moreover, I also checked the references.
Overall, this is a practical, timely framework with real-world potential, enhanced by the open calculator tool. With major revision to reorganize into full IMRaD structure (adding Discussion), expand references/introduction, provide methodological overview/justification/software details, and deepen comparisons/limitations/implications, it will be an excellent fit for Open Research Europe. I look forward to the revised version.

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Urban and peri-urban green, Natural Heritage, Contingent Valuation Method, Regional Development of Mountain and Semi Mountain Areas, Sustainable Small Cities, Sustainable Development, Environmental Economy, Ecosystem Services, Land use, Decarbonization, Delignification, coal transition, Disaster Risk Reduction, Civil Protection

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.