ARTICLE

DOI 10.52781/cmm.a084

The customization of technology readiness assessment processes based on the TRL scale: development of a methodology for the Brazilian Army

La personalización de los procesos de evaluación de la preparación tecnológica basados en la escala TRL: desarrollo de una metodología para el Ejército Brasileño

Abstract: Technology Readiness Assessment (TRA) based on the TRL scale is a process aimed at minimizing problems in defining the stage of maturation of technologies, as well as providing efficient communication between specialists, managers and other stakeholders in organizations that acquire products and systems of high technological level. In this context, the work analyzes the customization of the TRA process from the perspective of a focal organization. For this purpose, we use as a case study the DCT (Department of Science and Technology), focal organization of a network for the development of defense technologies and products within the Brazilian Army (EB). The data collected came from the bibliographic review (study of customizations made by reference organizations in the national and international scenarios) and empirical data from DCT programs. With this data, it was possible to propose a framework methodology in the TRL scale customized to the specificities of EB.

Keywords: innovation management; systems engineering; technology readiness; TRL; Brazilian Army.

Resumen: La Evaluación de la Preparación Tecnológica (EPT) basada en la escala TRL es un proceso que tiene como objetivo minimizar los problemas en la definición de la etapa de maduración de las tecnologías, así como proporcionar una comunicación eficiente entre especialistas, gerentes y otras partes interesadas en las organizaciones que adquieren productos y sistemas de alto nivel tecnológico. En este contexto, el trabajo analiza la personalización del proceso EPT desde la perspectiva de una organización focal. Para ello, se utiliza como caso de estudio el DCT (Departamento de Ciencia y Tecnología), organización focal de una red para el desarrollo de tecnologías y productos de defensa en el ámbito del Ejército Brasileño (EB). Los datos recolectados provienen de la revisión bibliográfica (estudio de personalizaciones realizadas por organizaciones de referencia en el escenario nacional e internacional) y de datos empíricos de los programas DCT. Con estos datos, fue posible proponer una metodología para enmarcar la escala TRL personalizada para las especificidades del EB.

Palabras-clave: gestión de la innovación; ingeniería de sistemas; preparación tecnológica; TRL; Ejército brasileño.

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Received: 26 May 2022
Approved: 24 Oct. 2022

COLEÇÃO MEIRA MATTOS
ISSN on-line 2316-4891 / ISSN print 2316-4833
http://ebrevistas.eb.mil.br/index.php/RMM/index

1 Introduction

The Research and Development (R&D) of high-tech products is often characterized by the integration of new components and subsystems that are in the state of the art, which entails great complexity and a high degree of uncertainty during the early phases of technological development (DAVIES *et al.*, 2011; MÖLLER; HALINEN, 2017).

Additionally, in these early phases, it is more challenging to accurately assess the stage of evolution of new technologies and the adequate level of maturity to integrate them, in order to conceive a novel product (OLECHOWSKI *et al.*, 2020). Despite these difficulties, these evaluations are important, because the integration of immature components and subsystems can result in increased costs and delay in R&D programs and projects of high-tech products (UNITED STATES, 2015). In addition, both the implementation and the evolution of such programs and projects usually depend on decisions by managers that lack specialized technical knowledge. In this context, the perceptions about technology maturation by actors from different backgrounds tend to be diffuse, hindering the common understanding about the stage of evolution of the technologies involved in the design of the desired product (SALAZAR; RUSSI-VIGOYA, 2021).

In order to mitigate the problems of estimating the maturation stage and the efficient communication of these stages among specialists, managers and other stakeholders in R&D activities, NASA developed, in the mid-1970s, the Technology Readiness Level (TRL) scale, which standardized the maturation of technologies into nine readiness levels (MANKINS, 2009).

NASA R&D activities generally target products of very high complexity, which involve many customized components and which are produced in a few units (sometimes a single unit), such as long-range telescopes and space rockets.

These characteristics are typical of Complex Product Systems (CoPS) (HOBDAY, 1998), which differ from mass-produced products, or commodities. As such, the nature of NASA products and organizational culture were considered in the development of the TRL scale. Thus, other central organizations with similar issues, but dealing with R&D projects of different natures and having disparate organizational cultures, began to customize the Technology Readiness Assessment (TRA) process according to their different contexts. As an example of organizations that have adopted this approach, the U.S. Department of Defense (DoD) (UNITED STATES, 2009), the U.S. Department of Energy (DoE) (UNITED STATES, 2011) the European Space Agency (ESA) (ESA, 2017) and, in Brazil, the DCTA (Department of Aerospace Science and Technology) (ROCHA; MELO; RIBEIRO, 2017) the AEB (Brazilian

Space Agency) (XAVIER *et al.*, 2020). These focal organizations are characterized by interacting in a large business and scientific research network, composed of small, medium and large companies, funding agencies, universities, research institutes, etc.

Despite the existence of different customized TRL evaluation processes, as far as the authors' knowledge is concerned, there are no studies that demonstrate how the customization of these processes can be carried out. Therefore, in order to fill this gap in the specialized literature, this article aims to explore the TRA process in focal organizations of a business and scientific research network that develop high-tech products. As a research question, the study proposes to answer: **how to customize the TRA process from the perspective of a focal organization?**

For this purpose, the DCT (Department of Science and Technology), a focal Organization of a network for the development of defense technologies and products within the Brazilian Army (EB), was used as a case study, which, by serving as the unit of analysis for this research question, enabled, additionally, the creation of a customized methodology for the EB particularities.

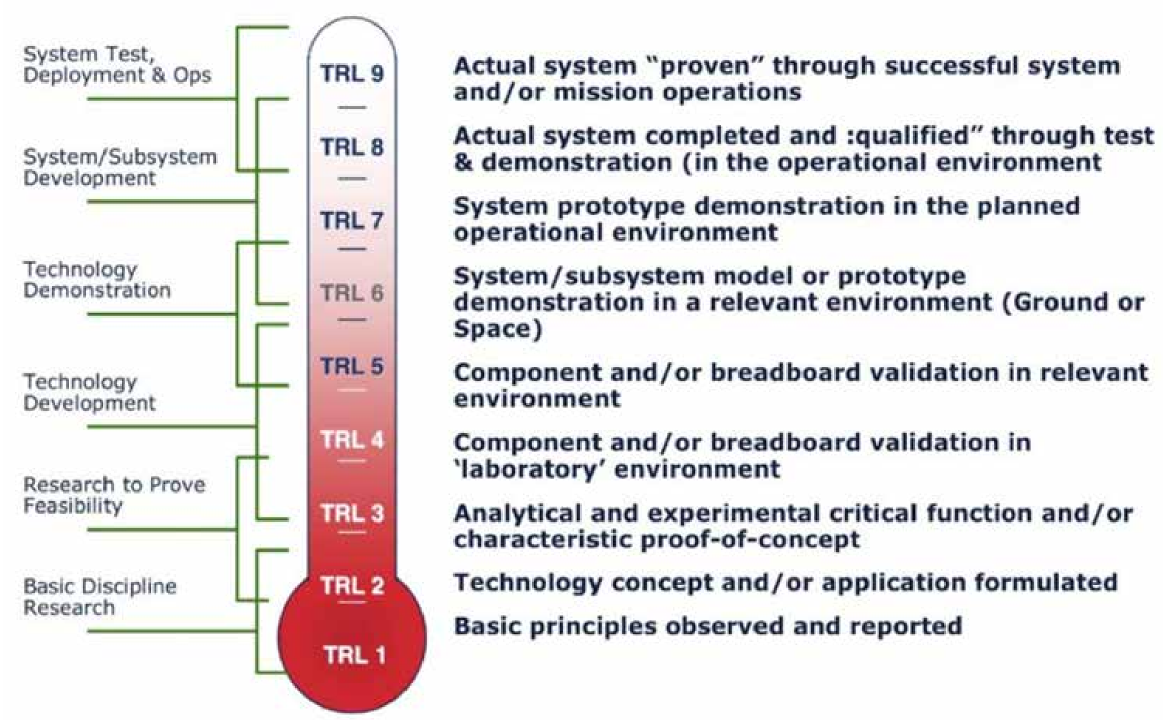
The rest of this article is organized as follows: Section 2 presents a bibliographic reference on the TRA process based on the TRL scale and issues of organizational culture and innovation that impact the process. Section 3 addresses the general methodological aspects used in the research. In Section 4, the framework methodology for the TRL scale customized for the EB is detailed. Section 5 discusses the results. Finally, the final considerations of the study are put in Section 6. It should be noted that the appendix contains a glossary with the definition of the terms used in the methodology described in Section 4.

2 Bibliography

2.1 The TRA process based on the TRL scale

In order to measure technology readiness in the development of space systems, the TRL tool was created. Developed in the mid-1970s by NASA, this tool provides a measure relative to the state of a new technology in relation to its use for future space systems. It was organized into nine (9) levels of readiness, as shown in Figure 1 (MANKINS, 2009).

Figure 1 – Technology readiness scale



Source: Mankins (2009).

The adoption of the TRL scale and a thorough set of procedures to infer about the level of readiness can be considered an impersonal interaction mechanism, as it establishes a common language and identifies critical milestones in the technology maturation process (SAUSER *et al.*, 2010). In this way, to improve communication between actors of a complex network, established to develop R&D projects in collaboration (SAUSER *et al.*, 2010), avoids false expectations about the development stage and minimizes risks in systems integration (GRANT, 1996).

There are other scales, but the one that has been used most frequently to systematically communicate the level of maturity of technologies to be incorporated into products and systems is the TRL (UNITED STATES, 2020a).

For this reason, over time, organizations have developed methodological frameworks over the TRL scale in order to meet their specific needs (JEAN; LE MASSON; WEIL, 2015) creating their own procedures for TRA. For example, the U.S. Government Accountability Office (GAO), the body of the legislative branch responsible for audit services, evaluations and investigations of Public Accounts of the United States government, establishes a guide with the following five steps for conducting TRA processes:

1) Structuring an TRA plan in the context of a procurement program or project: definition of the framework methodology on the TRL scale to be used, definition of TRA points throughout the life cycle (decision milestone), definition of the TRA team and its role in each of the decision milestones (purpose of the evaluations, reference values, possible paths after the evaluations, etc.);

2) Identify critical technologies: technology criticality has its own definitions and criteria, according to the organization context;

3) Evaluate critical technologies: assessment of the maturity level of critical technologies based on the framework methodology on the TRL scale;

4) Prepare an TRA report: consolidation of the results obtained during the evaluation of critical technologies; and

5) Use TRA report results: analysis and use of the report data in the development of a technology maturation plan (UNITED STATES, 2020a).

This GAO guide shows that the TRL scale is the tool that underpins the entire TRA process. This perception justifies the argument that the customization of the TRA process from the perspective of a focal organization begins with the customization of methodological framework over the TRL scale. This is the path taken by the DoD (UNITED STATES, 2009), DoE (UNITED STATES, 2011), ESA (ESA, 2017) and, in Brazil, by DCTA (ROCHA; MELO; RIBEIRO, 2017) and AEB (XAVIER *et al.*, 2020).

Aiming to adapt the original TRL scale to the characteristics of its programs and procurement projects, DoD developed a methodology for framing the TRL scale to assess the maturity of critical technologies (CTEs, Critical Technology Elements) in systems of hardware and software. In addition, the Department also has a methodology for the biomedical area developed by United States Army Medical Research and Materiel Command (USAMRMC). DoD combines the use of its methodology with the life cycle management of defense systems by referencing TRL levels for two decision milestones.

- **Milestone B**: marks the end of the phase of technology maturation and risk reduction. At the end of this phase, it is expected that all critical technologies have been demonstrated in a relevant environment (TRL 6);

- **Milestone C**: marks the end of the engineering and manufacturing development phase. At the end of this phase, it is expected that all critical technologies have been demonstrated in an operational environment (TRL 7) (UNITED STATES, 2009).

In order to simplify the determination of the appropriate TRL level for a technology, the AFRL (Air Force Research Laboratory), organization framed in the DoD organizational chart, developed a calculator that establishes specific steps that must be fulfilled for each level of the technology readiness scale. This tool contemplates the evaluation of three types of system elements: hardware, software, and hardware/software combined. The use of the calculator is carried out in two stages. In the first, a set of nine questions is applied for initial estimation of the TRL level of the technology. In the second, a detailed questionnaire is used to confirm whether the previously estimated TRL level is adequate. If confirmation does not take place, the procedure shall be repeated with the TRL level immediately lower. During the evaluation, a maximum of 58 (fifty-eight) questions are presented to the evaluator (NOLTE; KENNEDY; DZIEGIEL, 2003).

In the wake of DoD, DoE has made adaptations to the framework in the TRL scale to give greater focus to risk analysis in the energy area. Verification and validation of Safety Structures, Systems and Components (SSCs) were incorporated into the methodology as a way to mitigate risks for both workers in the sector and the general public. To operationalize the identification of the TRL level of a technology, the Department makes use of its own TRL calculator. This tool follows the two-step process (preliminary estimation and confirmation of maturity level), along the lines of the DoD calculator. During the evaluation, a maximum of 44 (forty-four) questions are presented to the evaluator (UNITED STATES, 2011).

In the European context, ESA has customized the framing methodology on the TRL scale for three distinct segments: space systems, ground systems and space-based software systems (ESA, 2020). In addition, the agency seeks to combine its methodology with the phases of the life cycle of its projects and with the elaboration of technology roadmaps. TRL level 6 is adopted as the minimum requirement for entry in the technologies integration phase (ESA, 2017).

In the Brazilian scenario, Rocha, Melo and Ribeiro (2017) present the customization carried out within the scope of DCTA. Seeking to adapt the original TRL scale to the Brazilian aerospace context, the TRL IAE-ITA methodology and its respective calculator were developed. The tool consists of a questionnaire with 89 (eighty-nine) questions divided into the following 5 (five) aspects:

- **NBR ISO 16290: 2015:** checklist the Brazilian standard for defining technology maturity levels for space systems (ABNT, 2015);

- **Technological:** relevant to the confirmation of the description of NBR ISO 16290: 2015;

- **Economic:** they address risk analysis and project development (schedule, budget, etc.);

- **Legal-political:** related to development feasibility, possibility of development embargoes, and legal issues; and

- **Documentary:** related to knowledge management, which must be documented, for possible reproduction (ROCHA; MELO; RIBIERO, 2017).

Following a similar approach, AEB developed a TRL calculator called IMATEC, to support decisions in the management of the Brazilian Space Program, more specifically the National Program of Space Activities. The agency customizes the TRL tool for use in conjunction with the Product Breakdown Structure (PBS). Creating a PBS and assessing the level of maturity of all components of a technological product makes it possible to exhaustively estimate the risk at a certain stage of development, given that the degree of readiness of an element of PBS will be the lowest TRL index of any of its constituent elements. Within this perspective, the components of PBS with the lowest TRL index are called "bottlenecks" of the product, since they propagate their low technology maturity indices to the framing elements in the PBS hierarchical tree. When assessing the TRL level of a PBS component, the calculator presents questions incrementally. If all questions on one level are answered positively, the questions on the next level follow. This procedure is performed until the TRL level is estimated. During the evaluation of each PBS component, a maximum of 14 (fourteen) questions are presented to the evaluator (XAVIER *et al.*, 2020).

In short, many organizations create their TRA methods according to their specific needs, without, however, modifying the essence of the original TRL scale. By the analysis carried out, it is verified that these processes of customization of the framework methodology in the technology readiness scale took into account two fundamental factors: adaptation to the organizational culture and the development of a TRL calculator.

- **Adaptation to organizational culture:** customization depends on the organizational culture of the business network to which the focal organization belongs and its technology management macroprocesses. For example, while the DoD frames TRA within the life cycle of its systems (UNITED STATES, 2009), the DCTA is concerned with issues related to technological, economic, documentary and legal-political matters (ROCHA; MELO; RIBIERO, 2017). In addition, despite the adoption of some areas of knowledge, such as systems engineering, each organization has different procedures related to planning, requirements management, R&D, testing, evaluation and certification, factors that directly impact the TRA process.

- **TRL Calculator:** during the analysis of the customization processes by the focal organizations studied, it was found that the development of the methodology is usually accompanied by the development of a calculator. In contrast to non-standard assessments, a calculator consisting of a standard set of questions simplifies the determination of the appropriate TRL level for a technology, as well as provides repeatability and consistency to the process (UNITED STATES, 2020a). Non-standard assessment of the readiness stage of a technology often leads to discrepancies between the TRL level perceived by different parties involved in a project (ALTUNOK; CAKMAK, 2010; FRERKING; BEAUCHAMP, 2016; MUDA; GOVINDARAJU; WIRATMADJA, 2022; NOLTE; KENNEDY; DZIEGIEL, 2003).

Table 1 summarizes the main customizations made by the focal organizations analyzed, according to the two factors listed.

Table 1 – Main customizations of the framework methodology in the TRL scale carried out by focal organizations that acquire high-tech products and systems

	Adaptation to organizational culture	TRL Calculator
DoD	• Suitability to the programs and projects management for obtaining defense systems; • Methodology for assessing the maturity of critical technologies in hardware, software and in the biomedical field; • Combines the use of the technology readiness scale with the life cycle management of defense systems, defining reference TRL levels for two decision milestones (TRL 6 for Milestone B and TRL 7 for Milestone C).	AFRL TRL calculator with 2-step process (preliminary estimation and maturity level confirmation). Tool with the maximum number of 58 questions.
DoE	• Suitability to project management in the energy area; • Focus on risk analysis; • Incorporates the Verification and Validation of Safety Structures, Systems and Components	Own TRL calculator with 2-step process (preliminary estimation and maturity level confirmation). Tool with the maximum number of 44 questions.
ESA	• Suitability for aerospace systems in the European context; • Methodology for three distinct segments: space systems, terrestrial systems, and software based systems; • Combines the use of the technology readiness scale with the phases of the project life cycle and the elaboration of technology roadmaps; • TRL Level 6 is adopted as a minimum requirement for entry into the technology integration phase.	Calculator development / employment is not reported.
DCTA	• Adequacy with the Brazilian standard NBR ISO 16290:2015; • Inserts issues related to technological, economic, documentary and legal-political issues.	TRL IAE-ITA calculator, tool with 89 questions divided into 5 questions (NBR ISO 16290:2015, technological, economic, documentary and legal-political).
AEB	• Adaptation to space systems in the context of the Brazilian Space Program; • Combines the framework methodology on the TRL scale with PBS; • Focus on risk analysis of projects related to the development of high-tech products.	IMATEC TRL calculator, tool with the maximum number of 14 questions for the evaluation of each of the PBS components.

Source: the authors (2022).

2.2 Aspects of organizational culture and innovation that impact the process

The concept of organizational culture refers to the shared values, beliefs, nomenclature, rituals, history, intellectual and operational traditions, pride in achievements, policies and practices, rules of conduct, philosophy, and other aspects that define an organization (GAYNOR, 2002). Organizational culture is conceived as a set of values and basic assumptions expressed in symbolic elements that, in their ability to order, assign meanings and build organizational identity, act as an element of communication and consensus (FLEURY; FISCHER, 1989).

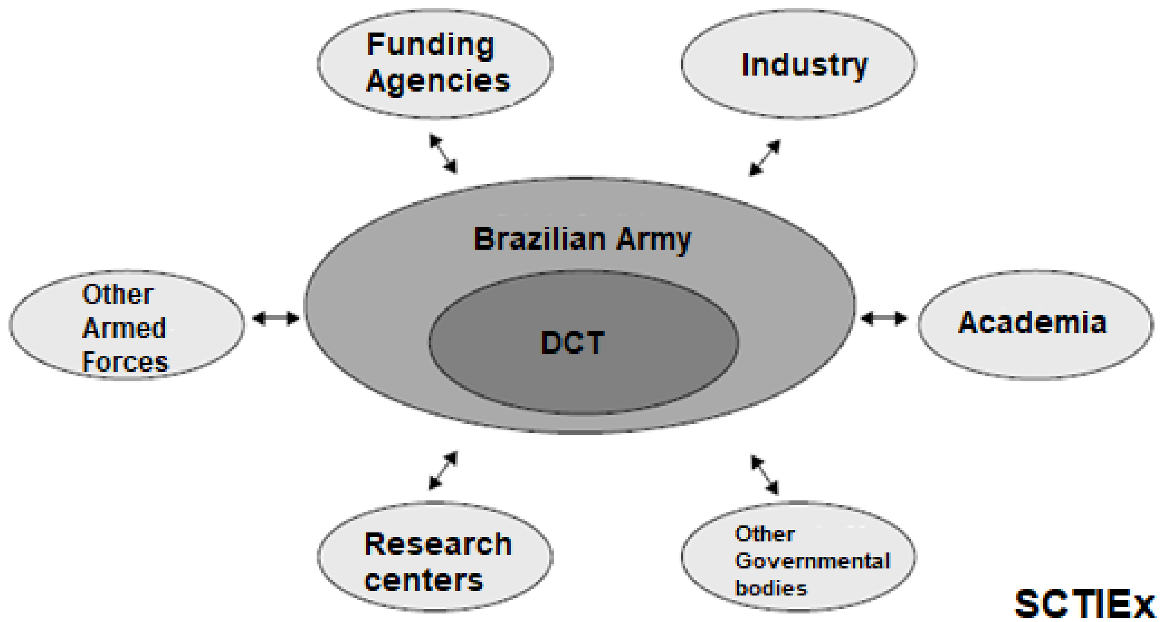
This search for accurate communication and consensus in the organizational environment has been addressed in the literature of organizational theory in different contexts, focusing, directly or indirectly, on mechanisms that contribute to increasing common understanding (FRANÇA JUNIOR; GALDINO, 2019). Promoting communication, integrating tacit knowledge and understanding different perspectives in complex networks composed of actors with diverse backgrounds and experiences are problems faced by organizations in charge of managing and carrying out R&D activities of high-tech products and systems (DAVIES *et al.*, 2011).

According to Schons, Prado Filho and Galdino (2022), studies carried out under EB have suggested that it is imperative to develop the capacity to carry out Science, Technology and Innovation (ST&I) activities in complex collaborative networks of national scope to strengthen the links between academia, industry and government (triple helix) (ETZKOWITZ; ZHOU, 2017) and undertake an open innovation model (CHESBROUGH, 2003) it replaces the traditional closed innovation model.

In this context, the Army Science, Technology and Innovation System (SCTIEx), a core element of the Brazilian defense sector, presents itself as a fundamental vector in the EB transformation process (FRANÇA JUNIOR; GALDINO, 2019).

For the design, planning and R&D phases of the life cycle of military equipment, EB has procedures, activities, methodologies, nomenclatures, standards and instructions specific to its organizational culture that end up being shared by the entire SCTIEx (LIMA, 2007). Figure 2 illustrates the SCTIEx structure, composed of military and civilian, public and private organizations that interact throughout the military material R&D process (BRASIL, 2012).

Figure 2 – Army Science, Technology and Innovation System



Source: adapted from Brazil (2012).

Therefore, in view of the particularities of the SCTIEx organizational culture (points detailed in Section 4), the need for customization of the framework methodology in the TRL scale was identified (FRANÇA JUNIOR; GALDINO, 2019), similar to the customizations undertaken by the focal organizations presented in Section 2.1.

3 Methodological aspects

The objective of this research was to explore the customization of the TRA process from the perspective of a focal organization. This goal was pursued from the perspective of a high-tech product development network. According to Dubois and Gadde (2002), research related to this type of network presents a series of interdependent variables that add complexity to the analysis. Similarly, Dubois and Gibbert (2010) argue that high-tech product development networks present researchers with particular challenges, since they do not constitute closed, delimited or clearly defined systems. In this context,

> The main units of analysis are organizations and relationships that are difficult to access and complex in structure in comparison, for example, with consumer markets. As a result, a case study of a single or a small number of such entities can provide a large amount of data, largely qualitative, that can be written as a case (EASTON, 2010, p. 118).

The case study can be considered as an in-depth and holistic description and analysis of a delimited phenomenon, such as a program, an institution, a person, a process or a social unit (MERRIAM, 1998). In this type of research, various methods of data collection and analysis are adopted to develop and understand the case, shaped by the context and emerging data (STAKE, 1995). As a qualitative method, case study research is a linear but also iterative process, involving the activities of planning, designing, collecting and analyzing data, investigating a contemporary phenomenon within its context (YIN, 2017). It is also considered more appropriate to study questions of "how" and "why", since they deal with operational links to be traced over time (YIN, 1994).

For this purpose, a case study was conducted using the SCTIEx network (BRASIL, 1994), in which DCT can be considered a focal organization. The actors in this network belong to quite diverse organizations, such as universities; small, medium and large companies; funding bodies; research institutes, in addition to the users of the developed products of the network themselves (FRANÇA JUNIOR; GALDINO, 2019).

DCT plays a key role in the life cycle management of defense products, especially in the conceptual formulation and procurement phases[1]. In this sense, this department has all the characteristics of a focal organization that needs to insert a technology maturity assessment process aligned with its high-tech product management macroprocesses. In addition, the scope achieved by SCTIEx regarding the diversity of actors and variety of products of interest makes this an emblematic case study, given that the customization in question requires the convergence of ideas between actors of varied backgrounds and understandings about technology.

3.1 Data Collection

In a first round of discussion of the TRL calculator customized for EB (fourth step of the diagram in Figure 5), a workshop was done, which was attended by several experts from DCT. Divided into 4 (four) focus groups, according to the affinity of the activities of their organizations, the experts were in charge of simulating the framework of critical technologies of their choice, in the calculator. The experts, their organizations and their affinities regarding the TRL ranges are presented in Table 2.

1 R&D and/or acquisition of system or material with the technical, operational and logistical characteristics established by EB (BRASIL, 2016).

Table 2 – Expert groups consulted in workshop conducted at the Military Institute of Engineering to study the proposed TRL calculator

Specialist profile	Nº of specialists	Organization	Groups and assigned TRL Track
Teachers, researchers, heads of divisions.	7	IME (Military Engineering Institute)	**Group 1:** affinity with basic and applied research; verification of technical feasibility.
Heads and experts in R&D projects.	5	CTEx (Army Assessment Center)	**Group 2:** affinity with technology development and demonstration.
Specialists in testing defense products.	2	CAEx (Army Assessment Center)	**Group 3:** affinity with product development; integration and testing; product in operation.
Specialists in defense product development contracting.	3	DF (Manufacturing Directorate)	
Experts in technological innovation.	3	AGITEC (Army Agency for management and technological innovation)	**Group 4:** affinity with the managerial aspect and macro vision.
Students of the Army Command and General Staff School.	2	ECEME (Army Command and General Staff School)	

Source: the authors (2022).

In the simulation, after analysis and discussion, the experts of each group answered the calculator questions and framed the technology under evaluation at a TRL level, presenting, at the end, the justifications for the framing. As a result of the discussions, questions, comments, criticisms and suggestions about the calculator questionnaire emerged, which led to the elaboration of a report, whose analysis allowed the refinement of the TRL calculator.

In a second discussion phase (sixth step of the diagram in Figure 5), we sought to apply the scale and questionnaire resulting from the previous step in real projects. Three ongoing programs were selected in the DCT, the Strategic Guideline Program for the Conceptual Formulation of Armored means of the Brazilian Army (PROJETO..., 2019), Software-defined Radio Program (PRADO FILHO; GALDINO; MOURA, 2017) and the Solo – Solo Missile

1.2 Program (BRASIL, 2020). These three programs were chosen because they are in different stages of development, as a consequence contemplating in the study critical technologies and subsystems in diverse stages of maturity, thus providing a complete analysis.

Some national defense companies involved with these programs, as well as organizations belonging to the DCT itself, were consulted. The list of the actors and their subsystems evaluated is shown in Table 3.

Table 3 – List of companies, technologies evaluated and experts interviewed

Technology provider organization	Technologies and subsystems evaluated	Number of experts interviewed	Position of experts
CTEx – Laboratory of Optronics	Thermal imaging monocular; GAZE and the Multispectral Assisted Vision System.	1	Project manager.
CTEx – Department of Information Technology	Vehicular Software Defined Radio.	5	Technical experts of the RDS project.
CTEx – Missile and Rocket Group	Solo-Solo Missile 1.2.	3	Head of the group, project manager and technical specialist.
CDS	Battlefield manager	1	Project manager.
ARES	Gyro stabilized platforms; software of graphic simulation application; explosives and ammunition; fire direction electronics; REMAX; REMAN; optical systems; and electro-optical systems.	5	Commercial and marketing director, 2 Project managers and 2 technical specialists.
OPTO	Universal vision system; Optical Periscope and Optronic Systems.	3	CEO, 1 Industrial manager and 1 Industrial Director.
Equitron	Slewing and lifting actuators; energy Pack; Batteries;Situational Awareness Camera System; Transfer case; Reversing box; Brake Assembly; Lock Differential; Control panel; Shooting Display and situational awareness; Shooting Joystick control; Integration Dam with Optronics– HMI.	2	Chief Executive Officer and 1 technical specialist.

Source: the authors (2022).

In the case of companies, technical visits and interviews with key members were carried out in order to frame the selected subsystems using the TRL calculator, in its improved version. In addition, the site visit of the products and production process was allowed in order to reinforce the information provided by the companies. During the interviews the focus was to identify the methods, types and test environments that were used for the subsystems, in order to identify some criterion not observed in the refined calculator.

In the case of DCT organizations, in addition to interviews and technical visits, the experts filled out the TRL calculator, classifying the maturity levels of the subsystems and thus performing a self-assessment. Then three workshops were carried out with the specialists of CTEx, as well as a consultation within the DCT framework, where it was possible to raise new criticism and suggestions for the refinement of the calculator.

3.2 Analysis of collected data

The data collected can be divided into two types: data from the bibliographic review and empirical data obtained from the study with specialists who work in DCT programs and projects.

The bibliographic review enabled the creation of Table 1, built from the analysis of customizations carried out in important focal organizations that develop complex products and systems, such as DoD (UNITED STATES, 2009), DoE (UNITED STATES, 2011), ESA (ESA, 2017), DCTA (ROCHA; MELO; RIBEIRO, 2017) and AEB (XAVIER *et al.*, 2020). As a result of this analysis, it was possible to conclude about the main factors that lead to the customization of the TRA process: organizational culture and framing method (TRL calculator).

Empirical data from interviews and workshops, served to include, adjust or remove criteria from the custom TRL calculator, according to the experts who used it at various stages of the customization process.

4 Methodological framework on the TRL scale for EB

As discussed by França Junior and Galdino (2019), the methodology for framing a technology at TRL scale levels needs to be customized according to the particularities of organizations working with high-tech systems, such as SCTIEx (FRANÇA JUNIOR; GALDINO, 2019).

Thus, we sought to create a methodology for the EB that takes into account the needs of this institution, such as: the evaluation of technologies developed by external organizations; the evaluation of technologies developed by their organizations in partnership with external organizations; strategic R&D planning; development risk analysis; use of information collected throughout the life cycle of products obtained through R&D by the system; and increase common understanding among diverse SCTIEx actors.

In this context, a methodological framework was developed in the TRL scale (summarized in Table 4) based on the customization factors identified in Table 1.

- **Adaptation to organizational culture:** seeking adherence to the General Instructions for Life Cycle Management of Military Systems and Materials (SMEM) (IG 01-018) (BRASIL, 2016), the adequacy of the methodological framework in the TRL scale was based on three aspects:

  I. The first aspect concerns the importance of inferring about the reproducibility of products produced in large quantities (UNITED STATES, 2020b), through the evaluation of a pilot batch [2]. EB generally does not deal with complex products produced in a few units, only. It employs products of varying degrees of complexity and production volume, ranging from those produced in tens and hundreds of units to those produced in mass. This aspect underpinned the **inclusion of TRL level 10** in methodology;

  II. The second aspect relates to the need for the gradual evolution of operational and technical requirements (OR and RTLI) [3]. Due to the long duration of the defense product development process, it is difficult to accurately predict, especially in the early stages, the architecture of complex products, which usually involves a large number of components and subsystems (DAVIES *et al.*, 2011). Thus, it is essential that the evolution in question occurs as the project advances in the TRL levels, allowing OR and RTLI to be updated at appropriate times, up to a certain TRL level, from which changes in requirements entail rework and extension of development deadlines; and

  III. The third and final aspect involves the user feedback during the doctrinal experimentation, after the adoption and distribution of the product, aiming at the information generation for its improvement or development of new versions (KIRSCHENBAUM *et al.*, 2020; LORD *et al.*, 2019; MUDA; GOVINDARAJU; WIRATMADJA, 2020; STRAUB, 2015). The organizational structure of EB allows data collection of defense products and systems in operation, by the user, thus facilitating the acquisition of important information to support decisions to initiate new research, perform improvements of technology demonstrators and prototypes of new versions of products and systems, as well as to promote improvements and

2 Experimental or preliminary production of a relatively small product, with the purpose of adapting the prototype and testing the respective production line (BRASIL, 2016).

3 In this methodology, it is adopted that, in order to achieve TRL 6 to 9, the approved OR and RTLI are necessary. As of TRL 6, the updating of requirements must be carried out sparingly and in an agreed manner between the technical and operational parties, in order to avoid rework. In addition, it is proposed that, for a more incremental and consistent evolution of the requirements, it is planned to prepare preliminary versions of the OR and RTLI already in TRL 4 and 5, only in the requirements that are related to the critical functions of these levels.

corrections of failures and bugs of the products and systems themselves and their eventual modernizations. This aspect underpinned the **inclusion of TRL level 11** in methodology.

- **TRL calculator development:** a calculator was developed in order to establish specific steps that must be met for each TRL level, as well as to identify the type of organization responsible for the criteria for achieving certain steps, such as the Science and Technology (S&T) bodies, responsible for the preparation of the conceptual formulation, the evaluation of prototypes and pilot batches and SMEM homologation; and the general management body (ODG), responsible for the preparation of operational requirements and adoption of SMEM.

Table 4 – Summary of the TRL scale framework methodology for EB

TRL level	Description
1	**Observed and reported basic principles / theoretical modeling:** documented studies dealing with basic scientific principles, in which potential applications can be identified.
2	**Technology concept and/or application formulated:** documented studies that analyze specific applications of the object (analysis of functionalities, performance and identification of experiments).
3	**Critical function experienced and analyzed in a laboratory setting:** documented studies of experiments demonstrating the feasibility of applying the object in a high-fidelity simulated environment (specification of functionalities, performance and experiments conduction).
4	**Proof of concept validated in a laboratory environment:** critical functions of the object, implemented in a concept proof, are tested in a laboratory environment.
5	**Validated engineering model in relevant environment:** critical functions of the object, implemented in an engineering model, are tested in a relevant environment.
6	**Technology demonstrator validated in relevant environment:** critical functions of the object, including performance parameters, dimensions and weight, implemented in a technology demonstrator, are tested in the relevant environment, established in accordance with Operational and Technical Requirements.
7	**Technology demonstrator integrated into the target product validated in operational environment:** demonstrator of the technology of the object is integrated into the target product and its critical functions are tested in a first prototype version, in operating environment and according to Operational and Technical Requirements.
8	**Prototype validated in operational environment:** the target product is tested considering almost all Operational and Technical Requirements. This level represents the end of product development.

TRL level	Description
9	**Prototype evaluated by competent body (prototype evaluation):** the target product is evaluated and approved by the competent bodies of the DCT in accordance with all its Operational and Technical Requirements.
10	**Repeatability of evaluated production (pilot batch evaluation):** pilot batch evaluated and approved by the S&T bodies and adopted by ODG.
11	**Product in operation / Feedback from processed user:** improved product with flaws and bugs corrected based on feedback of the user.

Source: the authors (2022).

Note: the glossary of methodology terms can be found at **Appendix**

It is important to note that up to Level 9, the TRL scale for EB is similar to the traditional TRL scale. At these levels, customization is restricted to the criteria that must be met in each of the nine levels, as described below.

Seeking the establishment of specific steps to be fulfilled at each level of technology readiness, a calculator was developed, in a web[4] environment, by the Agency for Management and Technological Innovation (AGITEC). The tool, which can be accessed on the Army corporate network (EBNet) by the address http://intranet.agitec.eb.mil.br/calculadora, allows you to frame a technology at a TRL level after completing a maximum of 11 (eleven) questions.

Despite the expanded scope in relation to the other applications found in the literature review stage (CoPS and mass-produced products), which implied the addition of two levels to the methodology, the development process was successful in obtaining a simple procedure. Simplicity is a fundamental characteristic for the intended ability to facilitate communication between a wide range of actors regarding areas of expertise and professional experiences.

On the basis of the calculator presented by Nolte, Kennedy and Dziegiel (2003), the application follows the process in two stages: preliminary estimation and confirmation of the level of maturity. In addition, in a similar way to the IMATEC calculator of the Brazilian Space Agency (XAVIER *et al.*, 2020), the evaluation of the TRL level of a technology is carried out in relation to a particular Target Product[5].

At the stage of preliminary estimation of the maturity level, as illustrated in Figure 3, the TRL range in which the object[6] is more likely to meet: initial studies (TRL 1 to 3); develop-

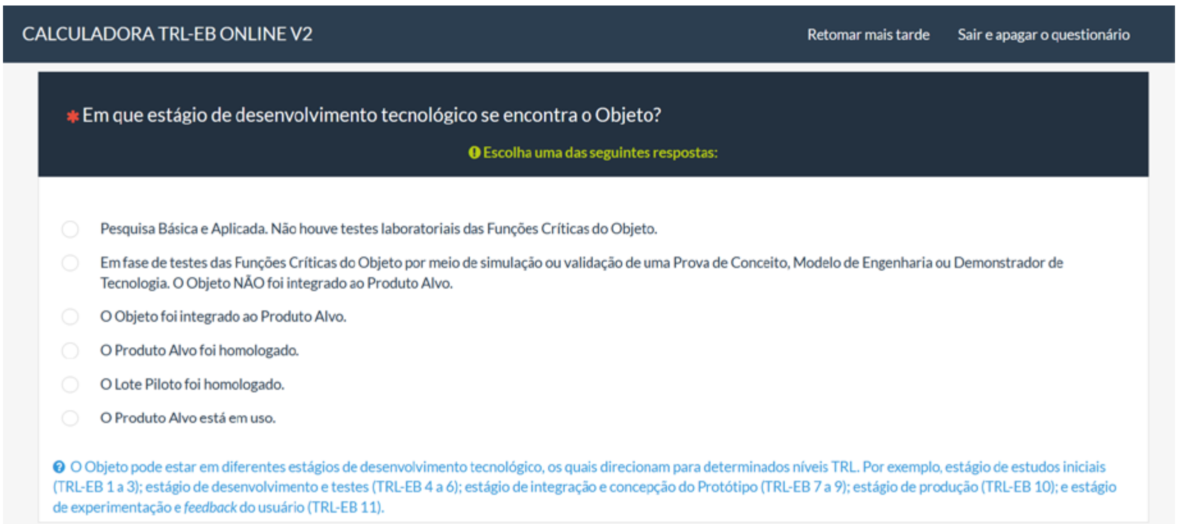
4 Name by which the World Wide Web (Internet) became known from 1991, when it became popular due to the creation of a graphical interface that facilitated access and extended its reach to the general public (OXFORD..., 2021).

5 Product or system that wants to be develop, composed of several critical and non-critical technologies.

6 "Object" refers to a critical technology, but can be represented by a system, subsystem or component (hardware or software) which, inserted in a hierarchical structure, integrates a system or product (Target product).

ment and testing stage (TRL 4 to 6); prototype integration, design and evaluation stage (TRL 7 to 9); production stage and evaluation of the pilot batch (level 10); and experimentation and user feedback (level 11).

Figure 3 – TRL ranges in which the object can be found (preliminary estimation step of maturity level)



Source: AGITEC Intranet.

In the confirmation step, the most appropriate level of the range identified from the validation of its indicators is chosen. The object is classified at the highest level in which all indicators have been met. The calculator indicators for each TRL level are summarized in Table 5.

Table 5 – Summary of indicators for each level in the TRL calculator for EB

TRL level	Indicators
1	• Definition of the basic scientific principles of the analyzed object as: formulation of laws, hypotheses, basic properties, theoretical principles or models; • Existence of potential practical applications related to the observed basic principles.
2	• Studies or industrial protection of the Object that analyze functionalities, performance and identification of experiments, for specific applications; • Definition of specific applications of the analyzed Object.
3	• Studies or artifacts of the Object that demonstrate experiments and that analyze functionalities, performance and results of experiments, for specific applications; • Demonstration of the feasibility of applications (e.g. laboratory bench or computer simulation with real data); • Identification of interfaces of the Object with other Objects.

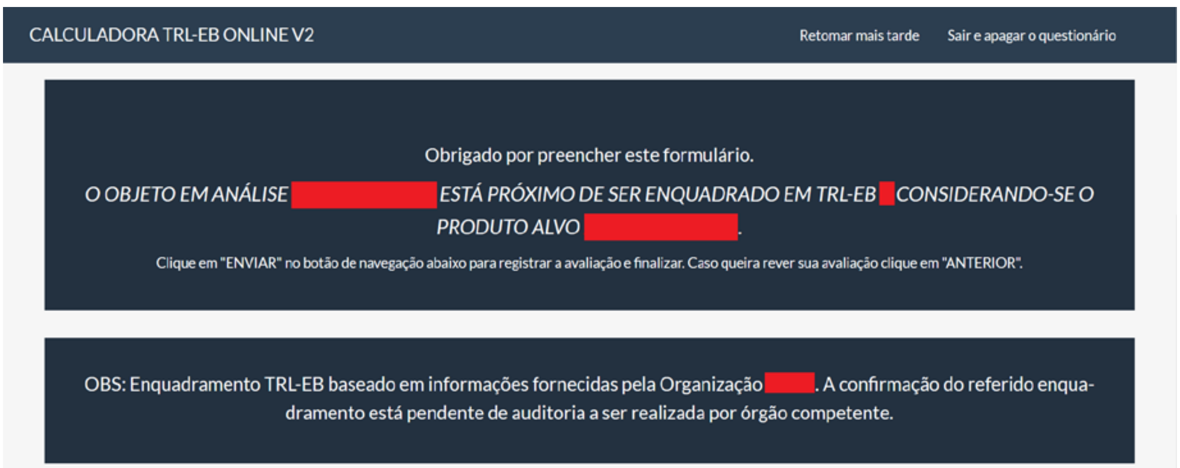
TRL level	Indicators
4	• Specification of the critical functions of the Object to be tested in a proof of concept and in a laboratory environment (laboratory environment critical functions); • Draft of preliminary OR and RTLI ; • Proof of concept test results in laboratory environment successfully validating performance and interface requirements.
5	• Specification of the critical functions of the Object to be tested in an engineering model and in relevant environment (critical functions of relevant environment); • Draft of preliminary OR and RTLI (with adjustments in relation to the version in TRL 4, if applicable); • Test results of the engineering model in relevant environment successfully validating performance and interface requirements.
6	• Specification of the critical functions of the demonstrator, to be tested in relevant environment, including those related to dimensions and weight (critical functions of relevant environment of the technology demonstrator); • COMOP, CONDOP (doctrinal and operational determinants), OR and RTLI of the target product for which the analyzed object is intended; • Technology demonstrator test results in relevant environment successfully validating performance, dimensions, weight and interface requirements, and conforming to the RTLI mapped in the relevant environment critical functions.
7	• Specification of the critical functions of the demonstrator, to be tested in the operational environment, including those that are only possible to be tested when it is integrated into the Target Product (critical operational environment functions); • Technology demonstrator test results in operating environment successfully validating performance and interface requirements and conforming to RTLI mapped in critical operational environment functions.
8	• Complete development of the target product prototype, which integrates the analyzed object, to be tested in an operational environment; • Prototype test results in operational environment successfully validating almost all absolute requirements of OR and RTLI.
9	• Prototype test results in operational environment successfully validating all OR and RTLI; • Assessment Report approved by competent S&T body.
10	• Experimental or preliminary batch of a product, relatively small, ready to be evaluated, for the purpose of testing the reproducibility of a low-scale production line; • Evaluation Report of pilot batch approved by competent S&T body; • Act of adoption of the Target Product.
11	• Doctrinal Experimentation Report; • New version of the Prototype in use, with the usage information duly implemented.

Source: the authors (2022).

Note: the glossary of methodology terms can be found at **Appendix**

After the validation of indicators in the second stage of filling, as illustrated in Figure 4, the calculator presents the TRL level in which the Object under analysis best fits, considering the associated Target Product. It should be noted that the framing carried out by the calculator is based only on the indication of documents proving the achievement of indicators for a certain TRL level. The confirmation of this framework requires an audit to be carried out by a competent body, if there is institutional interest in the technology.

Figure 4 – Framing result performed by the TRL calculator for EB



Source: AGITEC Intranet.

It is important to emphasize that the tool presents considerable maturity in terms of use within the army, given that the development process had two rounds/versions with great participation of ICT (Scientific, Technology and Innovation Institution) of EB. The calculator already counts 520 hits in its current version (Version 2).

5 Presentation and discussion of results

From the data presented, it was found that TRA based on the TRL scale is a process aimed at minimizing issues in defining the stage of technology maturation, as well as providing efficient communication between specialists, managers and other stakeholders in organizations that acquire high-tech products and systems.

With the TRL scale being the tool that underpins the entire TRA process, it was found that its customization from the perspective of a focal organization begins with the customization of the methodological framework over the TRL scale.

In the case of DCT, focal organization of a network for the development of defense technologies and products, the process of customization of the methodological framework over the TRL scale was phased in 9 (nine) stages:

1) Initial diagnosis: as presented in França Junior and Galdino (2019), it is necessary to carry out a diagnosis of the organization, aiming to identify its strengths, weaknesses, opportunities and threats; its characteristics, specificities and organizational culture; and the objectives intended with the implementation of a communication tool with the ability to standardize knowledge regarding the level of maturity of a given technology. In the DCT diagnosis, the need to customize the framework methodology on the TRL scale was identified, given that the original methodological approach did not fully meet the specifics of the organization. In this sense, two factors were pointed out as premises for the customization process:

a. Scope: broadening the product-related scope (from CoPS to mass-produced products) and focusing on communication among a wide range of stakeholders regarding areas of expertise and professional experience; and

b. Simplicity: development of a tool that is easy to access and operate and that facilitates the audit process of the evaluations carried out (FRANÇA JUNIOR; GALDINO, 2019);

2) Bibliographic review: analysis of customizations made by focal organizations that develop high-tech products and systems. In the DCT case study, the following focal organizations were analyzed: DoD (UNITED STATES, 2009), DoE(UNITED STATES, 2011), ESA (ESA, 2017), DCTA (ROCHA; MELO; RIBEIRO, 2017) and AEB (XAVIER *et al.*, 2020). As summarized in Table 1, this analysis identified two main factors for the customization of the framework methodology in the TRL scale: adaptation to the organizational culture and the development of a TRL calculator;

3) 1st Minute of the calculator: based on these two customization factors, a first draft of a TRL calculator for EB was prepared by a limited set of specialists;

4) Workshop for calculator discussion: in order to discuss the first draft of the calculator, a workshop with several experts from military organizations that work from basic research to the use of the product was held, therefore sweeping all ranges of the TRL scale;

5) New calculator (version 1): improvement of the calculator first draft from the discussions in the workshop.

6) Experimental usage in real cases: for the experimentation of the first version of the calculator, three ongoing programs were selected in the DCT, the strategic Guideline Program for the Conceptual Formulation of Armored means of the Brazilian Army (EB) (PROJETO..., 2019), the Radio Program defined by Software (PRADO FILHO; GALDINO; MOURA, 2017) and the Solo – Solo Missile 1.2 program (BRASIL, 2022). These three programs were chosen because they are in different stages of development, so their critical technologies, or subsystems, would be well distributed along the TRL scale, providing a complete analysis;

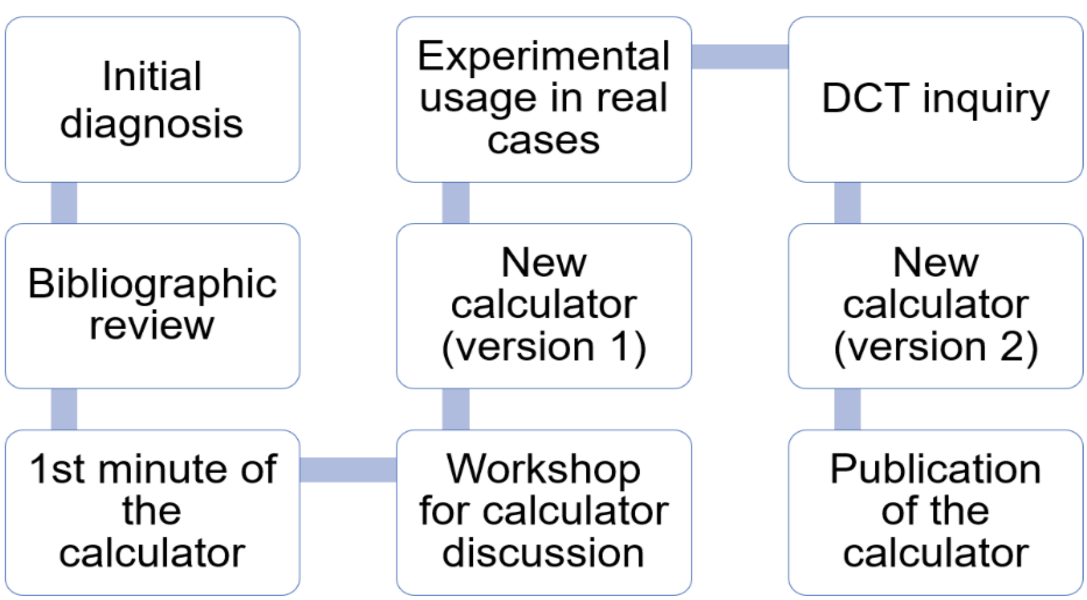
7) DCT inquiry: after the enhancement of the calculator with the workshop and with the experimental usage in real cases, a consultation was carried out within the scope of the DCT to validate the modifications;

8) New calculator (version 2): improvement of the calculator based on the information from the DCT consultation round; and

9) Provision of the calculator: finally, after the process of improvement and validation of the tool, the calculator was made available for use by the EB, accessible in the Army corporate network (EBNet) by the address http://intranet.agitec.eb.mil.br/calculadora.

The nine (9) steps of this customization process are represented in the Figure 5 diagram.

Figure 5 – Stages of the process of developing a framework methodology in the TRL scale for the Brazilian Army



Source: the authors (2022).

After providing a general overview about the customization undertaken in the EB context, it is necessary to discuss a few important points identified throughout the study.

5.1 Adherence to literature review

Firstly, the adherence of the case study to the bibliographic review should be highlighted. It was possible to verify that the two factors identified during the literature analysis – organizational culture and framework method (calculator) – were necessary and sufficient for the development of a framing methodology on the TRL scale customized for the peculiarities of the Brazilian Army.

In this context, a point that deserves attention in this paper is the description of the effort required for the development of the TRL calculator. As shown in Figure 5, this effort required nine steps and the involvement of dozens of actors. In the literature, the development effort of a TRL calculator is neither detailed nor measured.

5.2 Need for inclusion of additional levels

The adequacy of the methodology developed to the General Instructions for Managing the Life Cycle of SMEM (IG 01-018) (BRASIL, 2016) it was based on three aspects: inference capacity on the reproducibility of products produced in large quantities through pilot batch evaluation, the need for the gradual evolution of operational and technical requirements (OR and RTLI), and consideration of the user feedback during doctrinal experimentation, aiming at the improvement or development of new versions of products and systems.

Regarding the reproducibility of products produced in large quantities through pilot batch evaluation, it was possible to identify that the original TRL scale did not have this objective. The NASA R&D context is extremely complex, such as long-range telescopes or space rockets, which involves many customized components and few units produced (sometimes a single unit). These characteristics are typical for CoPS (HOBDAY, 1998), which differ from products produced in large quantities (UNITED STATES, 2020b). EB employs products of varying degrees of complexity and production volume, ranging from those produced in tens and hundreds of units, to those produced in mass. This wide range of products comprises radars, tanks, missiles, tactical radios, drones, light weapons, ballistic protective vests and ammunition. This aspect underpinned the **inclusion of TRL level 10** in the methodology, which refers to the repeatability of the evaluated production (pilot batch evaluation).

Another aspect not covered by the original TRL scale was the consideration of the user feedback. The Brazilian Army plans to take advantage of the user feedback during the doctrinal experimentation, after the adoption and distribution of the product, aiming at the generation of information for its improvement or development of new versions (KIRSCHENBAUM *et* *al.*, 2020; LORD *et al.*, 2019; MUDA; GOVINDARAJU; WIRATMADJA, 2020; STRAUB, 2015). The organizational structure of EB allows data collection of defense products and systems in operation (in use by the user), thus facilitating the obtaining of important information to support decisions to initiate new research, perform improvements of technology demonstrators and prototypes of new versions of products and systems, as well as to promote improvements and corrections of failures and bugs of the products and systems themselves and their eventual modernizations. This aspect underpinned the **inclusion of TRL level 11** in the methodology, which refers to the product in operation/processed user feedback.

5.3 Critical success factors

Throughout the development of a framework methodology on the TRL scale for EB, it was possible to identify two critical factors that enabled the achievement of an acceptable result to the effort undertaken: **multidisciplinary approach** and **favorable governance**.

As for the multidisciplinary approach, it should be noted that the participation of professionals from different areas of expertise (teaching, research, contracts, management, testing and evaluation, technological innovation and military doctrine) and backgrounds (military, civil servants and employees of Defense Industrial Base companies - BID) was of fundamental importance for the incorporation of different points of view in the methodology and establishment of a common communication base. In addition, the discussion and experimentation of the TRL calculator by different actors allowed the revision of its design, the removal of redundancies and the reconciliation of effectiveness with simplicity, considering that the TRL evaluation by the tool for EB is accessible (web environment) and easy operation (requires a maximum number of answers lower than that required by the calculators analyzed in the bibliographic review). Still in regard to simplicity, it should be noted that the application facilitates the audit processes, since it incorporates the indication of documents proving the achievement of indicators in the bulk of the evaluations.

In regard to favorable governance, the support of the top management of the Army Science and Technology area was crucial for the engagement of several professionals in the organization, as well as for the realization of consultation rounds that allowed the improvement of the methodology.

5.4 Generalization of the process of customization of the framework methodology in the TRL scale

From the bottom-up approach (WALDEN *et al.*, 2015), it is possible to extrapolate the customization process carried out under the DCT to a generic process to be undertaken by focal organizations that develop high-tech products and systems. This generic process can be represented by 3 (three) steps:

1) Diagnosis: carrying out the organization diagnostics, particularly in regard to its strengths, weaknesses, opportunities and threats; its characteristics, specificities and organizational culture; and intended objectives with the implementation of a communication tool that aims to standardize knowledge in respect to the level of maturity of a given technology. This diagnosis indicates two possible paths:

a. If the original approach does not fully meet the culture of the organization, the need to customize the framework methodology on the TRL scale is indicated;

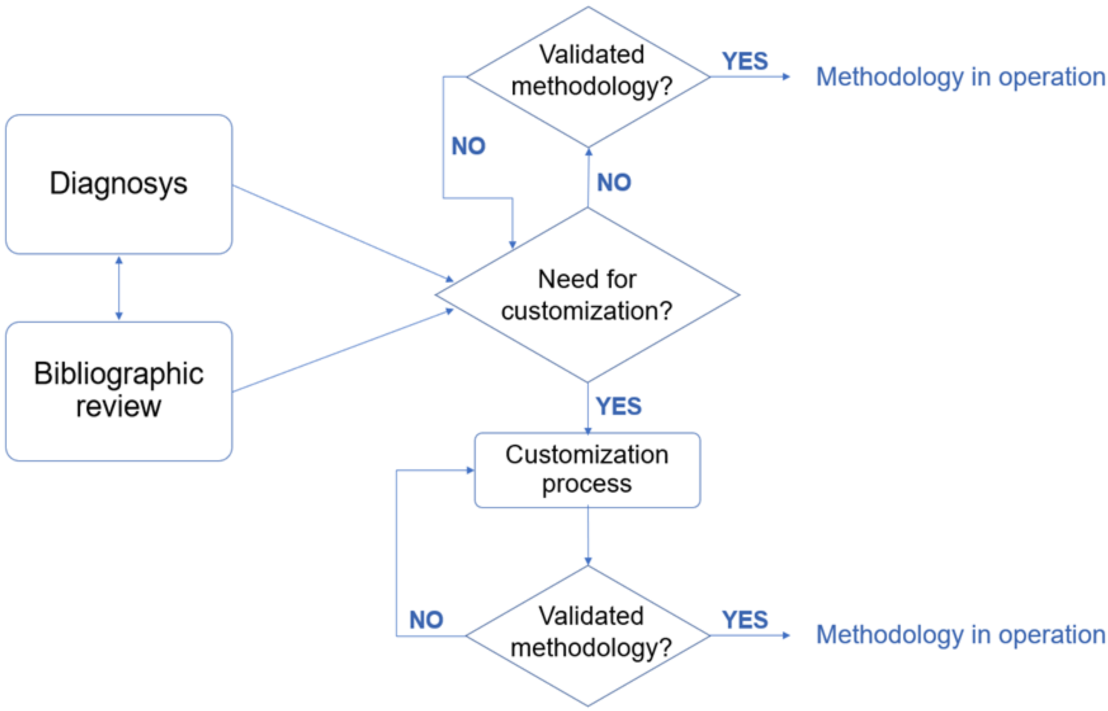
b. Otherwise, the possibility of adopting the original methodology by the organization is indicated. If necessary, minor adjustments can be made, e.g. translation and/or language adaptation;

2) Bibliographic review: in order to rectify or ratify the initial diagnosis, it is necessary to analyze processes of customization of the TRL scale undertaken by focal organizations that develop high-tech products and systems in order to understand the associated state of the art and build a comparative reference;

3) Iterative customization process: once the need for customization is confirmed, the process of developing a framework methodology on the TRL scale customized to the specifics of the organization should begin. The process is considered completed when the rounds of validation of the methodology within the organization are considered sufficient. It is suggested that the development of the methodology be accompanied by the implementation of a framework method (TRL calculator). This tool simplifies the determination of the appropriate TRL level for a technology, as well as provides repeatability and consistency to the process (UNITED STATES, 2020a). This is because non-standard assessment of the readiness stage of a technology often leads to discrepancies between the TRL level perceived by different parties involved in a project (ALTUNOK; CAKMAK, 2010; FRERKING; BEAUCHAMP, 2016; MUDA; GOVINDARAJU; WIRATMADJA, 2022; NOLTE; KENNEDY; DZIEGIEL, 2003).

The 3 (three) steps of the generic process of customization of the methodological framework in the TRL scale for focal organizations that develop high-tech products and systems are summarized in Figure 6.

Figure 6 – Generic process of customization of the framework methodology in the TRL scale for focal organizations that develop high-tech products and systems



Source: the authors (2022).

6 Final considerations

The present study revealed that the customization of the TRA based on the TRL scale is a laborious and complex process, and presented the first advances in the adaptation of the TRA to the life cycle management used by the EB (development of a methodological framework over the TRL scale).

The current scenario of specifying TRA processes is more widespread in economically and technologically developed countries, whose organizations manage to insert the maturation of critical technologies within life cycle management models and technology roadmaps of its products and complex systems (ESA, 2017; UNITED STATES, 2009, 2011).

Seeking this direction, countries with late development, as is the case of Brazil, whose high-tech demands are often not met internally, must customize the processes of TRA and systems life cycle management in order to reconcile short-and long-term strategies in obtaining and maturing critical technologies (FRANÇA JUNIOR; GALDINO, 2022).

Within this perspective, in the scope of TRA processes for the EB, the following topics stand out for future work: improvement of the life cycle management model/TRA processes with the aim of reconciling short and long-term strategies in obtaining and maturing critical technologies; definition of a method for selecting critical technologies; definition of a method for selecting TRA staff and their role throughout the decision milestones of the life cycle; definition of methods for maturing critical technologies; and customization of the methodology framework on the TRL scale for the evaluation of components and subsystems of hardware, software and/or the biomedical field.

In a broader context, the article proposed, based on the DCT case study, a generic process of customization of the methodological framework on the TRL scale for focal organizations developing high-tech products and systems. In this generalization effort, it is also possible to approach, in future works, the use of TRA based on the TRL scale as a management and communication tool in Sectoral Innovation Systems (SIS), such as, at national level, the SIS of oil and gas and agribusiness (SCHONS; PRADO FILHO; GALDINO, 2022).

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Appendix

Laboratory environment: controlled environment that allows you to test critical functions and evaluate the performance of a particular technology, subsystem or component.

Operating environment: a real-world environment that allows the evaluation of some or all of the operational requirements specified for the evaluation of a product.

Relevant environment: a test environment that incorporates aspects of a controlled environment and a real environment, allowing simulation of critical and non-critical functions of an engineering model or technology demonstrator.

Component: most basic element pertaining to a subsystem, engineering model, or proof of concept.

Technology demonstrator: subsystem or system that represents a critical technology. It can be seen as an evolution of an engineering model and is used to demonstrate its technical feasibility in an operational environment, in order to verify the most relevant technical specifications and operational requirements of the target product. e.g. electronic circuit for encapsulated data transmission and reception , in order to allow portability, complying with previous operational and technical requirements of performance, dimensions and weight.

Scientific documentation: document containing a scientific text intended to discuss phenomena not yet fully understood. It can be published in magazines, annals, congresses, etc.

Critical functions: main functions of the evaluated object. They are the main functionalities, of a subsystem or component, to be tested for each level of technology readiness. The amount of critical functionality increases as readiness levels are achieved. In this way, each TRL level (from 4 to 7) has a set of predefined critical functions that need to be successfully tested in order to reach said level.

Critical function of laboratory environment: these are the critical functions of a proof of concept to be tested in a laboratory environment, and that must be defined to achieve TRL 4. e.g. electronic circuit for transmitting and receiving data, assembled on protoboard being powered by external power supply and processing algorithm installed in desktop computer. This proof of concept has the critical function of transmitting and receiving encrypted data. It can be tested in the laboratory without the need to evaluate transmission distance and speed.

Critical function of relevant environment: it is the critical functions that should be tested in relevant environment.

In the case of an engineering model, these critical functions must include, in addition to those specified in TRL 4, other functions that represent even more of the real system to achieve TRL 5. e.g. electronic circuit for transmitting and receiving data assembled on a printed circuit board with integrated power supply, and power antenna, and processing algorithm installed on FPGA. This engineering model has the critical function of transmitting and receiving encrypted data at a specific distance and speed. It can be tested in open field in order to evaluate not only the transmission capacity, but also its distance and speed.

In the case of a technology demonstrator, these critical functions must include, in addition to those specified in TRL 4 and 5, those related to performance, weight and dimensions, thus defining a new set of critical functions to achieve TRL 6. e.g. electronic circuit for encapsulated data transmission and reception in order to allow portability, complying with previous requirements of performance, dimensions and weight. This technology demonstrator has the critical functions of transmitting and receiving encrypted data at a specific distance and speed and being integrable into a portable communication device. It must be tested in a relevant environment in order to evaluate its performance in terms of distance, speed and transmission capacity, in addition to having viable dimensions and weight to be integrated into a communication device that is portable.

Critical operational environment function: these are the critical functions of a technology demonstrator to be tested in an operational environment when integrated with the target product, and which must be defined to achieve TRL 7. In addition to the critical functions tested in TRL 6, other critical functions of the technology demonstrator should also be considered that are only possible to be tested when it is integrated into the target product. e.g. electronic circuit for transmitting and receiving data integrated into a portable communication device. This technology demonstrator when integrated with a portable communication device, must have the same critical functions as TRL 6, that is, transmit and receive encrypted data at a specific distance and speed and have dimensions compatible with the portability of the communication device to which it will be integrated. In addition, its transmission performance must be compatible with the processing capacity of the communication device.

Pilot batch: experimental or preliminary production of a relatively small product, with the purpose of adapting the prototype and testing the respective production line.

Engineering model: an arrangement of integrated components that provides a representation of a system/subsystem and that can be used to determine the feasibility of a proof of concept. It can be seen as an evolution of a proof of concept, where laboratory components and equipment are replaced by models close to the actual subsystem so that they can be tested in the relevant environment. e.g. electronic data transmission and reception circuit assembled on printed circuit board with integrated power supply, high power antenna, and processing algorithm installed on FPGA.

Object: refers to a critical technology, but can be represented by a system, subsystem or component (hardware or software) that, inserted in a hierarchical structure, integrates a system or product (target product).

Applied research: applied research with the aim of developing technologies or techniques to intervene and alter natural or social phenomena. It can be supported by basic research.

Basic research: also called pure research or fundamental research, it is about research whose objective is the advancement of scientific theories aimed at the prediction or understanding of natural or social phenomena. It has a purely theoretical nature that intends to expand the understanding of phenomena or behaviors without, however, seeking to solve or address any problems associated with such phenomena.

Target product: product or system that wants to be develop, composed of several critical and non-critical technologies.

Intellectual property: includes patents, trademarks, industrial designs, geographical indications etc.

Prototype: first version of the target product to be produced and operated. It aims to validate all specified technical and operational requirements.

Proof of concept: an arrangement of integrated components that aims to validate a scientific concept or the main functions of a technology (critical functions). Typically this arrangement is integrated with laboratory equipment and components and “shelf” components. e.g. electronic circuit for transmitting and receiving data, assembled on protoboard being powered by external power supply and processing algorithm installed in desktop computer.

Operational Requirements (OR): document that follows the doctrinal and operational conditions in the process of obtaining an SMEM, which consubstances the characteristics restricted to operational aspects.

Technical, Logistical and Industrial Requirements (RTLI): document that arises from the operational requirements and consists of fixing the technical, logistical and industrial characteristics that the system or material must have to meet the established operational requirements.

Preliminary OR: requirements that describe only the main operational functionalities of the application (or applications) that are related to the evaluated technology. These requirements are ideally elaborated in TRL 4 and 5 and can be elaborated by the development team itself if they have basic knowledge of the user needs, or these can be extracted from technical standards. e.g. for the object "data reception and transmission module", a preliminary OR for the applications "vehicle software defined radio" or "portable software defined radio" would be: "the radio must transmit and receive text, audio and video data, maintaining a link of at least 20 km and in direct view".

Preliminary RTLI: requirements that describe only the main technical functionalities of the application (or applications) that is related to the evaluated technology and its critical functions of the laboratory environment. These requirements are ideally elaborated in TRL 4 and 5 and can be elaborated by the development team itself if they have basic knowledge of the user needs, or these can be extracted from technical standards. e.g. For the object "data reception and transmission module", a preliminary RTLI for the applications "vehicle software-defined radio" or "portable software-defined radio" would be: the radio must transmit and receive data, ensuring the transfer of 300 (three hundred) kB in a maximum of three minutes when aimed directly at a range between 20 and 40 km.

Complex Product Systems (CoPS): capital goods, systems, networks, control units, packages of software, specific, high-cost, high-tech buildings and services (HOBDAY, 1998).

Subsystem: an arrangement of integrated components that performs a certain function within a system.

Critical technology: technology pertaining to a target product that is essential to the achievement of its mandatory operational and technical requirements. It can be an unprecedented technology, or not mastered in the country, whose obtaining (acquisition or development) is of extreme priority, according to criteria of availability in the national and international market, and logistical and operational vulnerability.

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