

## Technological Article

# Application of technology readiness levels (TRL) in the assessment of an R&D project in a Brazilian industrial automation company

Reinaldo Borsato Rodrigues<sup>a</sup>  , Matheus Henrique de Carvalho Silva<sup>a</sup>  ,  
Eduarda Gandini Calheiros<sup>a</sup>  , Sandra Miranda Neves<sup>a</sup>  , and  
Andréa Aparecida da Costa Mineiro<sup>a</sup>  

<sup>a</sup>Universidade Federal de Itajubá, Itajubá, Minas Gerais, Brasil



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 **Corresponding author**

Sandra Miranda Neves  
[sandraneves@unifei.edu.br](mailto:sandraneves@unifei.edu.br)

## Abstract

**Objective of the study:** This research analyzes the implementation of the Technology Readiness Levels (TRL) methodology for measuring technological maturity in an innovative R&D project of an industrial automation company, aiming for its integration into existing management processes. **Methodology:** The methodological approach consisted of qualitative and applied action research conducted in two iterative cycles, utilizing the IMATEC platform and the "TRL-Sense Guide" instrument, with data collected via document analysis, participant observation, and structured interviews with twenty stakeholders. **Main results:** The results revealed heterogeneous maturity in the project, where the Ultrasonic Transducer reached level TRL 9 after interventions, while the Printed Circuit Board was classified as TRL 5 due to technical integration and regulatory compliance challenges. **Relevance/ originality:** Theoretically, the study fills a gap by detailing TRL application in the Brazilian private industrial sector, expanding the focus beyond the military and governmental spheres. The originality lies in proposing a model that translates technological metrics into managerial language within a national industrial context little explored academically. **Social/ management contributions:** As a management contribution, the development of the "TRL-Sense Guide" stands out as a customized tool that assists in mitigating technological risks and strengthening strategic decision-making in R&D.

**Keywords:** Technology Readiness Levels (TRL), Research and Development (R&D), Project management, Innovation process.

Aplicação dos níveis de maturidade tecnológica (TRL) na avaliação de um projeto de P&D em uma empresa brasileira de automação industrial

## Resumo

**Objetivo do estudo:** Esta pesquisa analisa a implantação da metodologia Technology Readiness Levels (TRL) para a medição da maturidade tecnológica em um projeto inovador de P&D de uma empresa de automação industrial, integrando-a aos processos de gestão existentes. **Metodologia/ abordagem:** O percurso metodológico consistiu em uma pesquisa-ação qualitativa e aplicada conduzida em dois ciclos iterativos, utilizando a plataforma IMATEC e o instrumento "Guia TRL-Sense", com dados coletados via análise documental, observação participante e entrevistas estruturadas com vinte stakeholders. **Principais resultados:** Os resultados revelaram uma maturidade heterogênea no projeto, com o Transdutor Ultrassônico atingindo o nível TRL 9 após intervenções, enquanto a Placa de Circuito Impresso foi classificada em TRL 5 devido a desafios de integração técnica e conformidade normativa. **Relevância/ originalidade:** O estudo preenche uma lacuna teórica ao detalhar a aplicação do TRL no setor industrial privado brasileiro, extrapolando os âmbitos militar e governamental predominantemente explorados. A originalidade reside na proposição de um modelo que traduz métricas tecnológicas para a linguagem gerencial em um contexto industrial nacional pouco explorado academicamente. **Contribuições sociais/ para a gestão:** Por fim, destaca-se o desenvolvimento do "Guia TRL-Sense", ferramenta customizada que auxilia na mitigação de riscos tecnológicos e no fortalecimento da tomada de decisão estratégica em PD&I.

**Palavras-chave:** Technology Readiness Levels (TRL), Pesquisa e Desenvolvimento (P&D), Gestão de Projetos, Inovação.



INTRODUCTION

Digital transformation in organizations aims to fully leverage information technologies to bolster survival and drive organizational performance growth (Men et al., 2023). Within this framework, the capacity for innovation emerges as a pivotal competitive advantage, and the Technology Readiness Levels (TRL) methodology stands out as an essential tool for mitigating uncertainties and supporting technological risk management. Developed by the National Aeronautics and Space Administration (NASA), the TRL scale facilitates the assessment of a technology’s degree of maturity and is extensively applied in Research, Development, and Innovation (RD&I) programs to categorize the developmental status of technologies and inform strategic decisions (ANEEL, 2024). In Brazil, its application is encouraged and referenced by key instruments and funding agencies. Law 11,196/2005, known as the “Lei do Bem,” provides tax incentives that enhance the innovative potential of firms (Chagas de Medeiros, 2024). Agencies such as EMBRAPPI also utilize the scale to establish criteria for their projects, mandating specific maturity levels according to the respective call for proposals (EMBRAPPI, 2020; EMBRAPPI, 2024).

In the Brazilian landscape, innovation is not merely a technical choice but a necessity for survival amidst economic volatility. As Tigre (2006) notes, national companies face the challenge of transitioning from an imitative stance to a leading role in R&D, which necessitates more robust risk measurement tools. The methodology’s relevance reaches strategic sectors, such as the military, exemplified by its use by the Brazilian Air Force in Operation Cruzeiro (FAB, 2021), and is also validated in international contexts, such as the mapping of a hydrographic SONAR project between TRL levels 3 and 7 (Riordan et al., 2019). Although the TRL scale provides a standardized metric for tracking technological progress, the scientific literature often focuses on its macrostructural application in large government or aerospace programs (Olechowski et al., 2015; Yfanti & Sakkas, 2024). There remains, therefore, a theoretical and empirical gap regarding how this methodology integrates operationally into project management routines in technology-based private companies, where agility and uncertainty pose additional challenges. Given this, the following research question emerges: How can the TRL methodology be implemented to assess and manage the evolution of technological maturity in R&D&I projects, integrating with existing management processes in a technology-based company?

To address this question, the general objective of this study is to analyze the implementation of the TRL methodology for measuring the technological maturity level across the various stages of an innovative R&D project, based on its application in a Brazilian industrial automation company. To this end, the following specific objectives were defined: (i) present the contributions of implementing the TRL methodology in technology-based companies; (ii) identify the technological readiness levels at each stage and the technologies involved in the development of an R&D project; and (iii) validate the study through the implementation and verification of results in a real project, thereby integrating the methodology into the company’s existing management processes. As a delimitation, it is noted that the company’s current management processes are already established, and the goal is not to reinvent them, but rather to propose the integration of the TRL methodology as a complementary tool.

To achieve these objectives, the methodological procedure adopted was action research, conducted at a Brazilian Industrial Automation Company. The object of study chosen by managers and researchers was the development project for an Industrial Ultrasonic Sensor, a strategic product of high technological complexity for the company.

The conduct of this research is justified by multiple factors. Firstly, the relevance of the topic, given that while the TRL methodology is well-established in the aerospace sector, its use is

increasingly extended to various high-end product development areas. Additionally, there is the importance of the object of study: a company that holds innovative technologies with global impact potential, whose development analysis can highlight the competitiveness of the national industry. In the academic field, the research contributes by presenting new application possibilities for the TRL methodology and, as a technological contribution, proposes a new process integrated into the company’s management, which can be replicated in other projects.

The article is structured into six sections. The first section introduces the topic and presents the research objectives. The second section covers the theoretical framework. The third section describes the adopted methodology and the object of study. In the fourth section, the results are presented. The fifth section discusses the findings, and the sixth section presents the conclusions and the main contributions of the research.

THEORETICAL FRAMEWORK

Technology Readiness Levels (TRL)

The Technology Readiness Levels (TRL) methodology was developed by the National Aeronautics and Space Administration (NASA) to assess the maturity of technologies throughout their development. Its consolidation occurred with Mankins (1995), who organized the model into nine levels, ranging from the observation of basic principles (TRL 1) to the successful operation of an actual system (TRL 9). This structure, presented in Table 1, provides a common reference for communicating technological progress and supporting decisions in Research, Development, and Innovation (RD&I) projects (NASA, 2007; Mankins, 1995).

Table 1  
Original TRL Definitions

| TRL | Definition                                                                                    |
|-----|-----------------------------------------------------------------------------------------------|
| 1   | Basic principles observed and reported                                                        |
| 2   | Technology concept and/or application formulated                                              |
| 3   | Analytical and experimental proof-of-concept of critical characteristics and/or functions     |
| 4   | Component and/or breadboard functional verification in laboratory environment                 |
| 5   | Component and/or breadboard critical function verification in relevant environment            |
| 6   | System and/or subsystem prototype demonstration in a relevant environment on ground           |
| 7   | System prototype demonstration in a space environment                                         |
| 8   | Actual system completed and flight qualified through test and demonstration (ground or space) |
| 9   | Actual system flight proven through successful mission operations                             |

Note: Adapted from Technology Readiness Levels: A White Paper by J. C. Mankins, 1995, NASA Office of Space Access and Technology

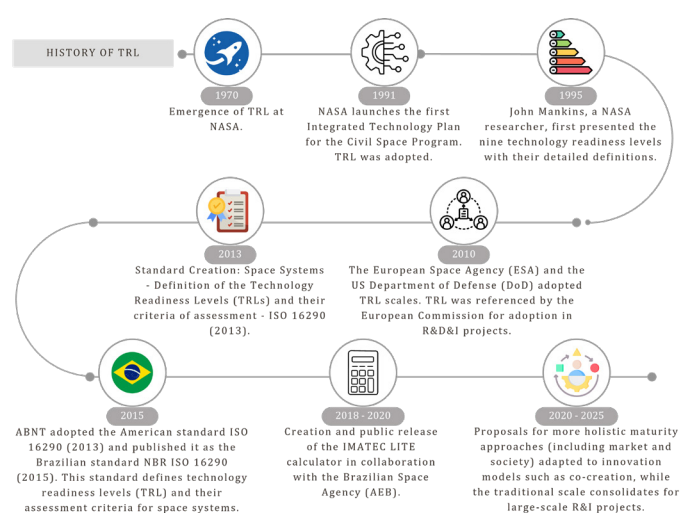
Although originally associated with the aerospace sector, TRL has been adapted to several fields, including biomedical systems, software, chemical processes, alternative energy, and underwater systems (Nolte & Kruse, 2011; Yasseri, 2016). Its adoption by institutions such as the U.S. Department of Defense, the European Space Agency, and the European Commission reinforced its use as a technological management instrument (EARTO, 2014; Office of the Under Secretary of Defense for Research and Engineering, Office of Systems Engineering and Architecture, 2025). This process also led

to the publication of ISO 16290, which formalized the definitions and assessment criteria for the scale. In Brazil, the standard was incorporated as ABNT NBR ISO 16290 in 2015 (ABNT, 2015).

Based on these criteria, Xavier Jr. et al. (2020) developed the IMATEC platform in partnership with the Brazilian Space Agency. The tool operationalizes the assessment of technological maturity through an online structure aligned with ABNT NBR ISO 16290. Figure 1 summarizes the main milestones in the development, dissemination, standardization, and expansion of the TRL methodology.

**Figure 1**

#### Historical Evolution of TRL



Note: Elaborated by the authors.

Despite its dissemination and standardization, TRL should not be interpreted as a complete or entirely objective measure of innovation maturity. The boundaries between levels may vary according to the sector and the assessment context, while technological development does not necessarily follow a unidirectional path. Technologies classified at advanced stages may require additional research and consequently return temporarily to a lower maturity level (EARTO, 2014).

These limitations have encouraged the development of broader assessment models. Vik et al. (2021) proposed the Balanced Readiness Level Assessment, which incorporates market, regulatory, acceptance, and organizational dimensions. Yfanti and Sakkas (2024), in turn, introduced a co-creation path for technologies whose advancement depends on interactions within a broader innovation ecosystem. These approaches indicate that technological maturity involves dimensions that extend beyond technical performance alone.

In the Brazilian industrial context, the main challenge lies in adapting the scale to organizational processes and sector-specific conditions. Studies by Rocha et al. (2017) and Santos (2023) indicate that the direct application of standardized criteria may require contextual adjustments, while IMATEC demonstrates how the requirements of ABNT NBR ISO 16290 can be translated into a structured assessment process (Xavier Jr. et al., 2020).

The reliability of this assessment also depends on the quality of the information shared by project teams. Psychological safety supports the reporting of failures, uncertainties, and technological limitations without fear of interpersonal consequences (Edmondson, 1999), reducing the risk of incomplete or artificially inflated maturity classifications. In this study, TRL is therefore understood as a management instrument whose effectiveness depends on contextualization, transparency, and integration with existing project management routines.

## Contextualization of TRL Application

International research has prioritized the expansion of the TRL scale to market, regulatory, and organizational dimensions (Vik et al., 2021; Yfanti & Sakkas, 2024). However, this structural approach often overlooks the practical challenges of integration and the inherent imprecision of technical assessment in corporate routines (Olechowski et al., 2015). In the Brazilian context, empirical studies on technology readiness remain nascent and focus primarily on formal assessments for funding agencies or the public and defense sectors (Bergamini, 2020; Xavier Jr. et al., 2020). This gap highlights the need to investigate how structured Project Management processes and team behavioral dynamics influence the transfer of technical knowledge, ensuring the reliability of maturity assessments in the private industrial sector.

The diffusion of TRL from its original conception in the aerospace field to multiple sectors, together with the adaptations developed for specific contexts, is well established in the literature (Li et al., 2021).

Current applications of TRL follow two primary avenues: direct assessment of technologies and the development of adapted frameworks to overcome the limitations of the original model.

In direct assessments, TRL is used as a benchmark to measure and compare the developmental stage of technologies in strategic sectors. This is exemplified by Sterner et al. (2024), who utilize TRL to compare green hydrogen import options; Solis and Silveira (2020), who evaluate technologies for the chemical recycling of plastics; and Suzianti et al. (2020), who measure the maturity of lithium battery technology in Indonesia. In these applications, the scale supports decision-making and the monitoring of a prototype's progress along the scale, such as a hydropower system or an industrial exoskeleton (Ahmad Mahauddin et al., 2024; Medina-Valdes et al., 2021).

The second application avenue arises from the limitations of a purely technical assessment. Researchers have proposed frameworks that expand TRL to specific contexts. Verma and Allen (2024), for instance, develop a sociotechnical model for the nuclear sector, while Van Cauwenbergh et al. (2022) propose an "institutional readiness" framework for nature-based solutions, and Greenwood et al. (2022) create a more granular version, the BC-RL, for battery components.

In Brazil, recent applied research (Bergamini, 2020) shows that TRL acts as a translation tool, converting engineering complexities and risks into managerial language understandable by project managers and decision-makers. However, Brazilian literature emphasizes that directly transposing the original scale is inadequate; its effectiveness requires customizations that reflect the team environment and local industrial innovation policies. Globally, researchers also propose context-specific frameworks, such as a socio-technical model for the nuclear sector (Verma & Allen, 2024), an "institutional readiness" framework for nature-based solutions (Van Cauwenbergh et al., 2022), and a granular BC-RL for battery components (Greenwood et al., 2022). The use of tools for analyzing technological maturity and the development of methodologies derived from TRL are also emphasized in the literature (Li et al., 2021).

In summary, whether applied directly or through adapted models, TRL has established itself as a central component in innovation management. Its use is essential for directing R&D investments more effectively, mitigating risks, and balancing an organization's portfolio of technology projects (Olechowski et al., 2015). However, empirical evidence on its operational integration into the routines of private Brazilian technology-based companies remains limited. This study addresses this gap by examining how technological evidence, Project Management routines, and stakeholder participation can be combined to support maturity assessment and strategic decision-making.

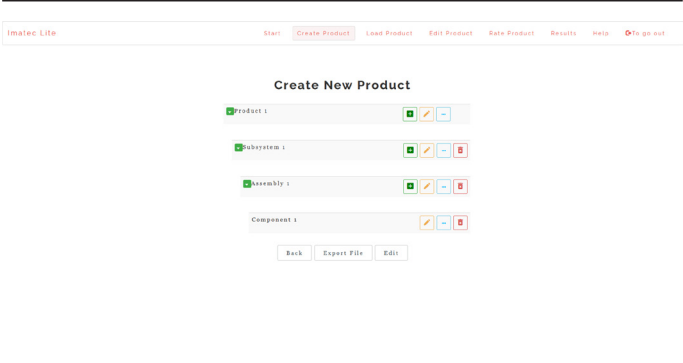
TRL Assessment Methods and Their Challenges

The application of TRL in research and development (R&D) projects directly depends on the use of appropriate assessment methods. The field of TRL study demonstrates continuous conceptual evolution. This diversity manifests in the creation of complementary scales, such as Manufacturing Readiness Levels (MRL), and, primarily, in the adaptation of calculation tools for different sectors and organizational approaches, as demonstrated by the works of Rocha et al. (2017) and Santos (2023). Consequently, the development and refinement of these tools constitute, in themselves, an active and relevant field of research.

In the Brazilian landscape, assessment tools have also been developed by public and defense institutions to support specific technological maturity evaluations. The MCTI, through Ordinance No. 6,449/2022, formalized the use of maturity calculators and provided an electronic assessment form as the official tool for projects funded by the Ministry (Brasil, 2022).

Among the prominent tools in Brazil is the IMATEC online platform (AEB Online Calculator for Assessing Technology Maturity), developed in partnership with the Brazilian Space Agency (AEB). Based on the criteria of the ABNT NBR ISO 16290 standard, IMATEC provides interactive queries and report export capabilities, proving suitable for use in supporting technological maturity assessment in technology-based R&D and innovation projects, as illustrated in Figure 2.

Figure 2  
IMATEC online platform for technological maturity assessment



Note: AEB (2020)

Despite the proliferation of tools, TRL implementation faces critical challenges. Olechowski et al. (2015) group these barriers into three main areas: system complexity, involving integration, interfaces, and scope; planning and review, related to alignment with the product life cycle and process trust; and assessment validity, which addresses the inherent subjectivity and imprecision of the scale. Overcoming these challenges requires the contextualization and specialization of the methodology for each specific project.

These challenges reinforce the need to adapt TRL assessment methods to the characteristics of each project. When integrated into R&D management processes, such tools can support the identification and management of technological risks throughout product development.

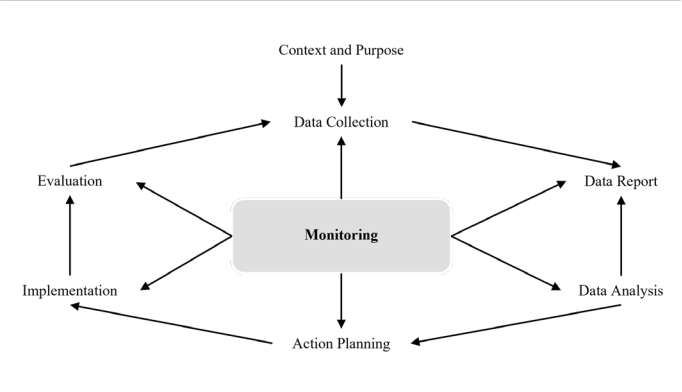
METHODOLOGY AND SAMPLE

Aiming to generate practical knowledge for solving a specific problem (Gil, 2019), this research was conducted using the action research method. The choice of this method is justified by its collaborative nature (Thiollent, 2005). The object of study was a Brazilian Industrial Automation Company, a technology-based company in the industrial automation sector, a national leader in its

field with significant R&D investment, supported by tax incentives such as the "Lei do Bem" (Law 11,196/2005). Despite its maturity in project management, utilizing, for instance, the PMBOK guide, the organization sought to formalize the measurement of technological risk and maturity. The choice of this organization was supported by its position in the domestic market and its continuous investment in R&D, providing a suitable setting for investigating innovation metrics in Brazilian industry.

Regarding ethical considerations, the research obtained formal organizational authorization to conduct interviews and observations. To preserve the confidentiality of strategic and technical information related to the evaluated technologies, a non-disclosure agreement was established. In addition, all participants formally acknowledged their participation through a free and informed consent term, ensuring the ethical handling of the information collected throughout the study. Given this scenario, the development project for an Industrial Ultrasonic Sensor was selected as the field of intervention. The operationalization followed the cycles of planning, action, and evaluation (Coughlan & Coghlan, 2002), as detailed in Figure 3. To ensure the credibility of the findings, triangulation of multiple data sources was employed: (i) analysis of technical project documents; (ii) participant observation, with one of the researchers acting as the lead engineer; and (iii) twenty structured interviews with the team, guided by the "TRL-Sense Guide" instrument (Appendix).

Figure 3  
Steps for Implementing Action Research as a Technical Procedure



Note: EAdapted from Coughlan and Coghlan (2002).

To ensure technical and managerial representativeness, the profile of the 20 participating stakeholders was defined based on their direct involvement in the project, as detailed in Table 2.

Table 2  
Profile of Stakeholders and Research Participants

| Quantity | Position / Role                            | Seniority / Average Experience      |
|----------|--------------------------------------------|-------------------------------------|
| 01       | Lead Engineer (Researcher)                 | > 10 years in Industrial R&D        |
| 01       | R&D Manager                                | > 15 years in Innovation Management |
| 01       | Industrial Manager                         | > 15 years in Production Processes  |
| 01       | Marketing Manager                          | > 10 years in Product Planning      |
| 16       | Technical Team (Engineers and Specialists) | Hardware, Software, and Mechanical  |

Note: Elaborated by the authors.

The content analysis of the data obtained from the interviews and observations was carried out using a structured coding process. The responses and evidence collected using the "TRL-Sense Guide" instrument were grouped into analytical categories defined by the normative axes of ISO 16290: (1) Functional Requirements, (2) Environmental Validation, and (3) System Integration. The interpretation of these data was conducted collaboratively between the researcher and the stakeholders. During the evaluation meetings, an environment of psychological safety was fostered, allowing the technical and managerial team to openly report uncertainties and technological failures without fear of repercussions. Differences in perception were resolved by consensus, transforming the qualitative data into final maturity scores and integrating the tool into the company's project management.

The intervention occurred in two cycles: in the first cycle, the IMATEC calculator was used to assess the "Ultrasonic Transducer" and "Transformer" sub-assemblies. In the second cycle, the process was refined by applying the same calculator in conjunction with the "TRL-Sense Guide" to reassess the components and analyze a new one, the "Printed Circuit Board". Monitoring was continuous through periodic meetings, allowing learning and reflection to inform subsequent actions throughout the cycles (Ballantyne, 2004). The specific process of this study was systematized into a methodological flow, presented in Figure 4.

**Figure 4**

*Methodological Flow of the Action Research Adopted in the Study*

|                          | Action Research Phases |                                   | Objective                                                                                                                      | Stakeholders                                                                       | Tool                  | Section in the Work |
|--------------------------|------------------------|-----------------------------------|--------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|-----------------------|---------------------|
| Action Research Planning | Pre-step               |                                   | Define problem, stakeholders, research scope, and methodology for problem-solving                                              | Researcher (Lead Engineer), Marketing Manager, R&D Manager, and Industrial Manager |                       | 4.1                 |
|                          | Data Collection        | Data Analysis and Action Planning | Determine the technology readiness level for the "Ultrasonic Transducer" and "Electroacoustic Coupling Transformer" subsystems | Researcher (Lead Engineer), Marketing Manager, R&D Manager, and Industrial Manager | AEB IMATEC CALCULATOR | 4.2                 |
|                          | Action Implementation  | Evaluation of Results             |                                                                                                                                |                                                                                    |                       |                     |
| Cycle 1                  | Monitoring             |                                   |                                                                                                                                |                                                                                    |                       |                     |
|                          | Data Collection        | Data Analysis and Action Planning | Determine the technology readiness level for the PCB system and its evaluation according to EMC/EMI criteria                   | Researcher (Lead Engineer), Marketing Manager, R&D Manager, and Industrial Manager | AEB IMATEC CALCULATOR | 4.3                 |
|                          | Action Implementation  | Evaluation of Results             |                                                                                                                                |                                                                                    |                       |                     |
| Cycle 2                  | Monitoring             |                                   |                                                                                                                                |                                                                                    | TRL-Sense Guide       |                     |

Note: Elaborated by the authors.

The data and findings resulting from the application of action research are detailed and discussed in the following section.

## RESULTS

The action phase of the research was conducted in two iterative cycles, aiming to implement and evaluate the TRL methodology within the project of an Industrial Ultrasonic Sensor—a highly complex product featuring technologies not yet fully mastered by the company.

### Mapping and Preparation for TRL Analysis

The first stage involved aligning the TRL methodology with the company's existing R&D processes. The "System" (product) was defined as the Ultrasonic Sensor, with the analysis focused on the "Electronic Project" subsystem. The "Assemblies" (technological blocks) selected for evaluation were the Ultrasonic Transducer (UT), the Electroacoustic Coupling Transformer (ECT), and the Printed Circuit Board (PCB).

To operationalize the assessment, the nine levels of the TRL scale, according to the ABNT NBR ISO 16290 standard (ABNT, 2015), were translated into the product development life cycle stages already established at the company. This mapping, which guided the entire data collection process, is synthesized in Table 3.

**Table 3**

*Relationship between TRL and the Stages of the Product Development Life Cycle in the Study Object*

| Technological Readiness Level (TRL) | Product Development Stage at the Study Object Company | Data Collection Questions                                                                                                                                                                                                                                                                                      |
|-------------------------------------|-------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| TRL 1                               | Provision of input data and Kick-Off meeting          | (1.1) Has the cognitive phase of creation been completed?                                                                                                                                                                                                                                                      |
| TRL 2                               | Pre-prototype idealization                            | (2.1) Has the cognitive phase of scientific investigation (formulation of ideas) been completed?                                                                                                                                                                                                               |
| TRL 3                               | Pre-prototype execution                               | (3.1) Have functional tests and simulations been completed?<br>(3.2) Have guiding scientific measures been identified?<br>(3.3) Has a critical function proof-of-concept been finalized analytically or experimentally?                                                                                        |
| TRL 4                               | Bench-Prototype                                       | (4.1) Was experimental laboratory research conducted?<br>(4.2) Were critical functional and performance parameters for the component derived from scientific measurement requirements?<br>(4.3) Did laboratory tests show that the development model meets the critical functional and performance parameters? |
| TRL 5                               | Prototype - LIT                                       | (5.1) Was experimental research conducted in a relevant environment (simulated space)?<br>(5.2) Were critical functional and performance parameters of the components validated in the relevant environment?                                                                                                   |
| TRL 6                               | Prototype - LIT (full tests)                          | (6.1) Was the component demonstrated in a relevant environment (simulated space)?                                                                                                                                                                                                                              |
| TRL 7                               | Customer Testing - Prototype                          | (7.1) Was the prototype demonstrated in an operational environment?                                                                                                                                                                                                                                            |
| TRL 8                               | Customer Testing - Pilot                              | (8.1) Was the component qualified in tests and demonstrations in an operational environment?                                                                                                                                                                                                                   |
| TRL 9                               | Validation                                            | (9.1) Is the component in operation or has it been successfully operated?                                                                                                                                                                                                                                      |

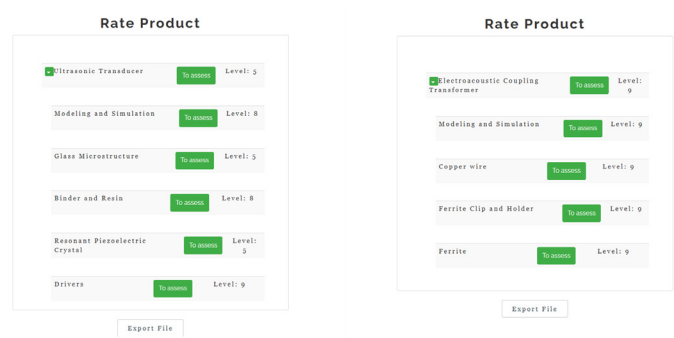
Note: Elaborated by the authors.

### First Action Cycle: Initial Maturity Diagnosis

In the first action cycle, conducted in October 2021, the research sought to assess the maturity of the technologies essential to the sensor. The team identified that project maturity was not uniform, presenting distinct technological risks for each subsystem. The initial diagnosis, detailed in Figure 5, revealed differences between technologies already mastered by the company and new R&D challenges.

Data interpretation shows that the ECT assembly reached full maturity (TRL 9), representing a consolidated technology ready for production. Conversely, the Ultrasonic Transducer (UT) exhibited heterogeneous maturity. Although modeling was advanced (TRL 8), critical components such as the "Resonant Piezoelectric Crystal" were positioned at TRL 5. This indicated that despite laboratory validation, the component represented the primary bottleneck for the final product's viability, requiring priority attention.

**Figure 5**  
*Initial Maturity Diagnosis – Cycle 1 (Side A: UT Assembly / Side B: ECT Assembly)*



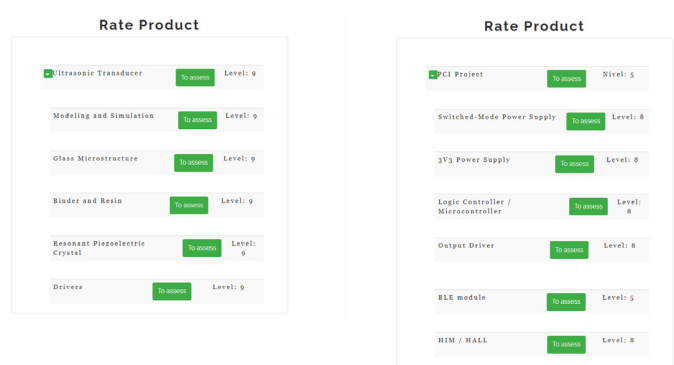
Note: Elaborated by the authors via IMATEC (2021).

Document analysis and participant observation identified the causes of this technical stagnation. During the iterative sessions of the first cycle, the researcher acted as lead engineer, mediating between the development team (hardware and mechanical specialists) and management. A direct comparison between bench test reports and the requirements of the “TRL-Sense Guide” revealed that the piezoelectric crystal exhibited response instability when subjected to severe thermal stresses. Stakeholders agreed that, although the critical function had been validated in isolation (TRL 4), the lack of adequate shielding and mounting in a relevant environment prevented the subsystem from advancing, confirming the empirical diagnosis of TRL 5.

Second Action Cycle: Maturity Evolution and PCB Analysis

Four months after the initial diagnosis, in February 2022, the second cycle allowed for monitoring the effectiveness of corrective actions and included the Printed Circuit Board (PCB). This stage represented the progression from laboratory development to industrial scale. As demonstrated in Figure 6, the maturity of the previously analyzed assemblies increased.

**Figure 6**  
*Evolution and Systems Integration – Cycle 2 (Side A: UT Reassessment / Side B: PCB Project)*



Note: Elaborated by the authors via IMATEC (2022).

The UT reassessment showed that the assembly reached TRL 9. This advancement was driven by the qualification of the Piezoelectric Crystal with strategic partners, mitigating the risk identified in the previous cycle. Simultaneously, PCB analysis

revealed that, although its internal components (microcontrollers and drivers) possessed high market maturity (TRL 8), the complete assembly was classified as TRL 5. This disparity resulted from the need to validate the proprietary architecture in a relevant environment, specifically regarding compliance with EMC/EMI standards, ensuring that component integration did not generate electromagnetic interference failures.

The project management team addressed this issue by mapping technical interdependencies. Laboratory reports indicated that the initial board layout allowed for high-frequency noise coupling, affecting the Bluetooth Low Energy (BLE) communication modules, which individually operated at TRL 8. The decision to classify the entire assembly as TRL 5 was made collectively after the engineering team demonstrated the risk of failure in official certification tests. The TRL-Sense Guide made it possible to translate a purely electromechanical constraint into a managerial indicator of project risk, informing strategic decision-making without masking integration uncertainties.

DISCUSSION

The application of TRL identified technological maturity at different project stages, validating its utility as a diagnostic tool. Stakeholder perceptions at the end of the process were consolidated into three points: (a) TRL is an effective tool for mitigating technological risks; (b) at lower TRLs, the methodology allows for development redirection, while at higher TRLs, it guides refinement; and (c) the TRL structure is simple and effective as an auxiliary management tool.

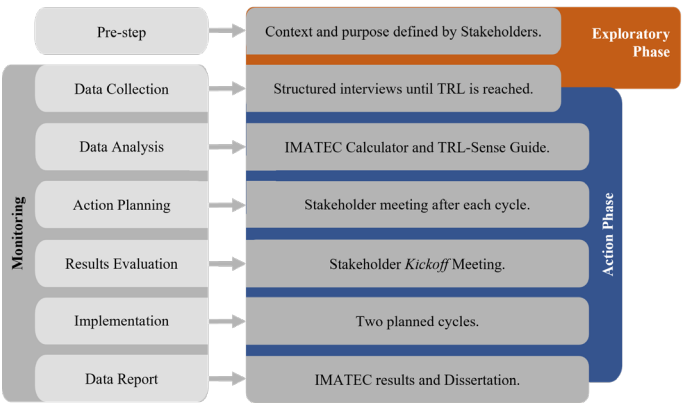
The effectiveness perceived by stakeholders in using TRL to mitigate technological risks aligns with Tigre (2006). The author argues that innovation management in Brazil must transition from informal processes to governance models that allow the detailed monitoring of each evolutionary stage of a product, which is consistent with the workflow implemented in this action research.

Beyond the technical results, the action research revealed that the transition from an “engineering project” mindset to a “technological maturity” perspective requires a cultural shift within the team, given the inherent subjectivity in perceiving readiness compared to the rigor of the ABNT NBR ISO 16290 standard. The Brazilian industrial dynamics, focused on short deadlines, conflicted with the analytical nature of the IMATEC calculator. This conflict served as the catalyst for the primary practical contribution of this study: the “TRL-Sense Guide”.

In addition to instrumental customization, the reliability of the assessment was also associated with the psychological safety (Edmondson, 1999) fostered within the project teams. The willingness of technical experts to report regulatory failures and critical bottlenecks (such as crystal instability and EMC/EMI noise in the PCB) without facing sanctions or pressure from commercial deadlines contributed to the accuracy of the diagnosis. This demonstrates that knowledge transfer mechanisms and technological maturity metrics require transparent and collaborative Project Management governance. Such transparency can reduce the risk of artificially inflating technological maturity assessments. This customized tool streamlined measurement and integrated the methodology into the company's processes, demonstrating that successful TRL implementation depends on its adaptation to organizational reality and existing management practices. Figure 7 summarizes the complete structure of the implemented action research.

Figure 7

Summary of the Implemented Action Research



Note: Elaborated by the authors via IMATEC (2022).

CONCLUSION

This research has demonstrated that the implementation of the Technology Readiness Levels (TRL) methodology is a viable and effective strategy for assessing and managing technological maturity in R&D projects. By integrating it into the existing management processes of a technology-based company, the study addressed its established objectives. By making technological risk visible and measurable, the methodology proved to be a strategic management tool that enhances control over the innovation process and strengthens decision-making.

Academically, the study contributes to filling a literature gap by providing a detailed case of TRL application within the Brazilian private industrial sector—a context that remains under-explored, as previous studies have predominantly focused on military and governmental sectors. As its primary managerial and technological contribution, the research validated a model for integrating TRL into R&D processes and resulted in the development of the "TRL-Sense Guide." This guide functions as an adaptable tool that demonstrates how the methodology can be adapted to organizational reality and may support other companies seeking to maximize the efficacy of their innovation investments. In this sense, the applicability of the model transcends sensor development, showing potential for application in the capital goods sector and other industrial automation verticals. In complex systems, such as machine tools or robotic cells, the technological decomposition logic adopted in this study can support the identification of bottlenecks in critical technologies before the completion of detailed design, assisting in the transition from customized projects to off-the-shelf products with controlled risks.

A recognized limitation of the study is the inherent subjectivity in assigning TRL levels, a factor mitigated by the use of structured checklists and cross-validation among the 20 stakeholders. Furthermore, the methodology was applied to an R&D project that was already in an intermediate stage of development, making it impossible to conduct empirical monitoring from the initial cognitive stages (TRL 1 and TRL 2).

Future research could employ longitudinal studies to monitor the complete life cycle of a technology, from basic research to market introduction. Additionally, quantitative studies could examine whether Project Management variables and levels of Psychological Safety within teams impact the speed of transition and the accuracy of TRL metrics in the national innovation ecosystem.

Conflict of interest statement

The authors declare that there is no conflict of interest.

Authors' statement of individual contributions

| Roles                      | Contributions   |                      |                 |                  |                     |
|----------------------------|-----------------|----------------------|-----------------|------------------|---------------------|
|                            | Rodrigues R. B. | Carvalho Silva M. H. | Calheiros E. G. | Miranda Neves S. | Costa Mineiro A. A. |
| Conceptualization          | ■               |                      |                 |                  |                     |
| Methodology                | ■               |                      |                 |                  |                     |
| Software                   | ■               | ■                    | ■               |                  |                     |
| Validation                 | ■               |                      |                 | ■                | ■                   |
| Formal analysis            | ■               |                      |                 | ■                | ■                   |
| Investigation              | ■               | ■                    | ■               | ■                | ■                   |
| Resources                  | ■               |                      |                 |                  |                     |
| Data Curation              | ■               |                      |                 |                  |                     |
| Writing - Original Draf    | ■               | ■                    | ■               | ■                | ■                   |
| Writing - Review & Editing | ■               | ■                    | ■               | ■                | ■                   |
| Visualization              | ■               | ■                    | ■               | ■                | ■                   |
| Supervision                | ■               |                      |                 | ■                | ■                   |
| Project administration     | ■               |                      |                 | ■                | ■                   |
| Funding acquisition        |                 |                      | N.A             |                  |                     |

Note: Acc. CRediT (Contributor Roles Taxonomy): <https://credit.niso.org/>

Open Science: Data availability

The entire dataset that supports the results of this study has been made available on SciELO Data from the REGEPE Entrepreneurship and Small Business Journal and can be accessed at the following DOIs:

| Badge | Description                                                                                             |
|-------|---------------------------------------------------------------------------------------------------------|
|       | Not applicable                                                                                          |
|       | Not applicable                                                                                          |
|       | Not applicable                                                                                          |
|       | <a href="https://doi.org/10.14211/regepe.esbj.e2899pr">https://doi.org/10.14211/regepe.esbj.e2899pr</a> |
|       | Not applicable                                                                                          |

REFERENCES

Agência Espacial Brasileira. (2020). *IMATEC: Calculadora de maturidade tecnológica*. <https://imatec.aeb.gov.br/#/home>

Agência Nacional de Energia Elétrica. (2024). *Guia de avaliação da maturidade tecnológica da ANEEL*. ANEEL. <https://www.gov.br/aneel/pt-br/assuntos/programa-de-pesquisa-desenvolvimento-e-inovacao/guia-de-avaliacao-da-maturidade-tecnologica-da-aneel>

- Ahmad Mahauddin, H., Jauhari, I., Nik Ghazali, N. N., Mohd Sultan, N., & Julai, S. (2024). Development and performance testing of a new in-pipe hydropower prototype towards Technology Readiness Level (TRL) 6. *Cogent Engineering*, 11(1), 2319402. <https://doi.org/10.1080/23311916.2024.2319402>
- Associação Brasileira de Normas Técnicas. (2015). *Sistemas espaciais — Definição dos níveis de maturidade da tecnologia (TRL) e de seus critérios de avaliação* (Norma ABNT NBR ISO 16290:2015). ABNT.
- Associação Brasileira de Pesquisa e Inovação Industrial. (2020). *Manual de operação EMBRAPII: Unidades EMBRAPII* (Versão 6.0). EMBRAPII. [https://embrapii.org.br/wp-content/uploads/2025/01/Manual\\_EMBRAPII\\_UE\\_versao-6.0-de-20.10.20.pdf](https://embrapii.org.br/wp-content/uploads/2025/01/Manual_EMBRAPII_UE_versao-6.0-de-20.10.20.pdf)
- Associação Brasileira de Pesquisa e Inovação Industrial. (2024). *Manual de operação dos centros de competência - PPI* (Versão 3.0). EMBRAPII. <https://storage.googleapis.com/uploads-site-embrapii/2024/12/Manual-de-Operacao-EMBRAPII-Centros-de-Competencia-PPI-Rev-3.0.pdf>
- Ballantyne, D. (2004). Dialogue and its role in the development of relationship specific knowledge. *Journal of Business & Industrial Marketing*, 19(2), 114–123. <https://doi.org/10.1108/08858620410523990>
- Bergamini, R. L. (2020). Avaliação do nível de maturidade de tecnologia (TRL) nas Instituições de Ciência e Tecnologia (ICTs) com o modelo adaptado da AFRL – Air Force Research Laboratory. *Revista de Administração de Roraima*, 10. <https://doi.org/10.18227/2237-8057rarr.v10i0.5738>
- Brasil. Ministério da Ciência, Tecnologia e Inovações. (2022, 19 de outubro). *Portaria MCTI nº 6.449, de 17 de outubro de 2022. Dispõe sobre o uso do sistema de medição e identificação do nível de maturidade tecnológica dos projetos desenvolvidos no âmbito do Ministério da Ciência, Tecnologia e Inovações e de suas unidades vinculadas*. Diário Oficial da União, Seção 1, 31. <https://www.in.gov.br/en/web/dou/-/portaria-mcti-n-6.449-de-17-de-outubro-de-2022-437609158>
- Chagas de Medeiros, A. B. (2024). O desenvolvimento tecnológico no Brasil: Desafios e oportunidades que a Lei do Bem gera para as empresas. *Caderno Virtual*, 1(58). <https://www.portaldeperiodicos.idp.edu.br/cadernovirtual/article/view/7684>
- Coughlan, P., & Coghlan, D. (2002). Action research for operations management. *International Journal of Operations & Production Management*, 22(2), 220–240. <https://doi.org/10.1108/01443570210417515>
- Edmondson, A. (1999). Psychological safety and learning behavior in work teams. *Administrative Science Quarterly*, 44(2), 350–383. <https://doi.org/10.2307/2666999>
- European Association of Research and Technology Organisations. (2014). *The TRL scale as a research & innovation policy tool: EARTO recommendations*. EARTO. [https://www.earto.eu/wp-content/uploads/The\\_TRL\\_Scale\\_as\\_a\\_R\\_I\\_Policy\\_Tool\\_-\\_EARTO\\_Recommendations\\_-\\_Final.pdf](https://www.earto.eu/wp-content/uploads/The_TRL_Scale_as_a_R_I_Policy_Tool_-_EARTO_Recommendations_-_Final.pdf)
- Força Aérea Brasileira. (2021, 16 de dezembro). *Operação Cruzeiro: FAB realiza primeiro teste de voo do motor aeronáutico hipersônico 14-X*. <https://www.fab.mil.br/noticias/mostra/38395/>
- Gil, A. C. (2019). *Métodos e técnicas de pesquisa social* (7ª ed.). Atlas.
- Greenwood, M., Wrogemann, J. M., Schmuck, R., Jang, H., Winter, M., & Leker, J. (2022). The Battery Component Readiness Level (BC-RL) framework: A technology-specific development framework. *Journal of Power Sources Advances*, 14, 100089. <https://doi.org/10.1016/j.powera.2022.100089>
- Li, H., Guo, H., Li, Z., & Wei, Q. (2021). A conceptual technology readiness loop model through systematic review and thematic synthesis. *Turkish Journal of Computer and Mathematics Education*, 12(11), 1687–1695. <https://doi.org/10.17762/turcomat.v12i11.6103>
- Mankins, J. C. (1995). *Technology readiness levels: A white paper*. NASA, Office of Space Access and Technology, Advanced Concepts Office. [https://space.nasa.gov/SEM/SEMModules/Technology%20Mod%20Mankins\\_trl.pdf](https://space.nasa.gov/SEM/SEMModules/Technology%20Mod%20Mankins_trl.pdf)
- Medina-Valdes, J. L., Zúñiga-Avilés, L. A., Cruz-Martínez, G. M., Vilchis-González, A. H., & Silva-Rivera, U. S. (2021). Study to increase the TRL of exoskeleton ERMIS based on a methodology to the identification of real performance parameters. *Applied Sciences*, 11(19), 9245. <https://doi.org/10.3390/app11199245>
- Men, F., Dong, F., Liu, Y., & Yang, H. (2023). Research on the impact of digital transformation on the product R&D performance of automobile enterprises from the perspective of the innovation ecosystem. *Sustainability*, 15(7), 6265. <https://doi.org/10.3390/su15076265>
- National Aeronautics and Space Administration. (2007). *NASA systems engineering handbook* (NASA/SP-2007-6105, Rev. 1). NASA Headquarters. [https://soma.larc.nasa.gov/mmx/pdf\\_files/NASA-SP-2007-6105-Rev-1-Final-31Dec2007.pdf](https://soma.larc.nasa.gov/mmx/pdf_files/NASA-SP-2007-6105-Rev-1-Final-31Dec2007.pdf)
- Nolte, W. L., & Kruse, R. (2011, 26 de outubro). *Readiness level proliferation* [Conference presentation]. 14th Annual Systems Engineering Conference (NDIA), San Diego, CA. [https://ndia.dtic.mil/wp-content/uploads/2011/system/13132\\_NolteWednesday.pdf](https://ndia.dtic.mil/wp-content/uploads/2011/system/13132_NolteWednesday.pdf)
- Office of the Under Secretary of Defense for Research and Engineering, Office of Systems Engineering and Architecture. (2025). *Technology readiness assessment guidebook*. U.S. Department of Defense. <https://www.cto.mil/wp-content/uploads/2025/03/TRA-Guide-Feb2025.v2-Cleared.pdf>
- Olechowski, A. L., Eppinger, S. D., & Joglekar, N. (2015). *Technology readiness levels at 40: A study of state-of-the-art use, challenges, and opportunities* (SSRN Working Paper Series). <https://doi.org/10.2139/ssrn.2588524>
- Riordan, J., Flannery, F., Toal, D., Rossi, M., & Dooley, G. (2019). Interdisciplinary methodology to extend technology readiness levels in SONAR simulation from laboratory validation to hydrography demonstrator. *Journal of Marine Science and Engineering*, 7(5), 159. <https://doi.org/10.3390/jmse7050159>
- Rocha, D., Melo, F. C. L., & Ribeiro, J. (2017). Uma adaptação da metodologia TRL. *Revista Gestão em Engenharia*, 4(1), 45–56. <http://www.mec.ita.br/~cge/RGE/ARTIGOS/v04n01a04.pdf>
- Santos, W. B. M. (2023). *Adaptação e implementação de ferramenta para avaliação do nível de maturidade tecnológica no segmento alimentício, com ênfase na área de pescado* [Dissertação de mestrado, Universidade Federal Rural do Rio de Janeiro]. Repositório Institucional da UFRJ. <https://rima.ufrjr.br/jspui/handle/20.500.14407/11046>
- Solis, M., & Silveira, S. (2020). Technologies for chemical recycling of household plastics – A technical review and TRL assessment. *Waste Management*, 105, 128–138. <https://doi.org/10.1016/j.wasman.2020.01.038>
- Sterner, M., Hofrichter, A., Meisinger, A., Bauer, F., Pinkwart, K., Maletzko, A., Dittmar, F., & Cremers, C. (2024). Import options for green hydrogen and derivatives — An overview of efficiencies and technology readiness levels. *International Journal of Hydrogen Energy*, 90, 1112–1127. <https://doi.org/10.1016/j.ijhydene.2024.10.045>
- Suzianti, A., Dewi, A. P., Mubarak, A., & Shafira, N. D. (2020). Technology readiness level assessment of lithium battery in Indonesia for national electric vehicle program. *AIP Conference Proceedings*, 2227(1), 040010. <https://doi.org/10.1063/5.0001010>
- Thiollent, M. (2005). *Metodologia da pesquisa-ação* (14ª ed.). Cortez.
- Tigre, P. B. (2006). *Gestão da inovação: A economia da tecnologia no Brasil*. Elsevier.
- Van Cauwenbergh, N., Dourojeanni, P. A., van der Zaag, P., Brugnach, M., Dartee, K., Giordano, R., & Lopez-Gunn, E. (2022). Beyond TRL – Understanding institutional readiness for implementation of nature-based solutions. *Environmental Science & Policy*, 127, 293–302. <https://doi.org/10.1016/j.envsci.2021.09.021>
- Verma, A., & Allen, T. (2024). A sociotechnical readiness level framework for the development of advanced nuclear technologies. *Nuclear Technology*, 210(9), 1722–1739. <https://doi.org/10.1080/00295450.2024.2336355>
- Vik, J., Melås, A. M., Stræte, E. P., & Søråa, R. A. (2021). Balanced readiness level assessment (BRLa): A tool for exploring new and emerging technologies. *Technological Forecasting and Social Change*, 169, 120854. <https://doi.org/10.1016/j.techfore.2021.120854>
- Xavier Jr, A., Veloso, A., Souza, J., Kaled Cás, P., & Cappelletti, C. (2020). AEB online calculator for assessing technology maturity: IMATEC. *Journal of Aerospace Technology and Management*, 12, e1320. <https://doi.org/10.5028/jatm.v12.1098>
- Yasseri, S. F. (2016). A measure of subsea systems' readiness level. *Underwater Technology*, 33(4), 215–228. <https://doi.org/10.3723/ut.33.215>
- Yfanti, S., & Sakkas, N. (2024). Technology readiness levels (TRLs) in the era of co-creation. *Applied System Innovation*, 7(2), 32. <https://doi.org/10.3390/asi7020032>

## APPENDIX

## Technical and Technological Production: TRL Guide Adapted to the Product Development Life Cycle

| NOTE: Reapply the guide for each component, assembly, subsystem, and system, and update the IMATEC tool. |                                              |                                                                                                                                                                                                          |                         |               |                |
|----------------------------------------------------------------------------------------------------------|----------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------|---------------|----------------|
| <b>Tool link:</b> <a href="https://imatec.aeb.gov.br/#/home">https://imatec.aeb.gov.br/#/home</a>        |                                              |                                                                                                                                                                                                          | PRELIMINARY<br>DOCUMENT |               |                |
| <b>Involved (Stakeholders):</b> SAB, RBR, AP.                                                            |                                              |                                                                                                                                                                                                          |                         |               |                |
| <b>Date:</b> 11/02/2022                                                                                  |                                              |                                                                                                                                                                                                          |                         |               |                |
| <b>Estimated next evaluation:</b>                                                                        |                                              |                                                                                                                                                                                                          |                         |               |                |
| <b>Project:</b> AD: Version: REV 0                                                                       |                                              |                                                                                                                                                                                                          |                         |               |                |
| <b>Subsystem:</b> Electronic Design                                                                      |                                              |                                                                                                                                                                                                          |                         |               |                |
| <b>Assembly:</b> PCB Design                                                                              |                                              |                                                                                                                                                                                                          |                         |               |                |
| <b>Component:</b>                                                                                        |                                              |                                                                                                                                                                                                          |                         |               |                |
| Technology Readiness Level                                                                               | Development stage                            | Questions (all must respond)                                                                                                                                                                             | Achieved?               | Justification | Pending issues |
| TRL 1                                                                                                    | Provision of input data and Kick-off meeting | (1.1) Was the cognitive creation phase concluded?                                                                                                                                                        |                         |               |                |
| TRL 2                                                                                                    | Pre-prototype conceptualization              | (2.1) Was the cognitive phase of scientific investigation (formulation of ideas) concluded?                                                                                                              |                         |               |                |
| TRL 3                                                                                                    | Pre-prototype execution                      | (3.1) Were functional trials and simulations concluded? (3.2) Were guiding scientific measures identified? (3.3) Was a proof of concept of a critical function finalized analytically or experimentally? |                         |               |                |
| TRL 4                                                                                                    | Benchtop Prototype                           | (4.1) Was experimental laboratory investigation performed?                                                                                                                                               |                         |               |                |
|                                                                                                          |                                              | (4.2) Were the critical functional and performance parameters of the component derived from scientific measurement requirements?                                                                         |                         |               |                |
|                                                                                                          |                                              | (4.3) Did laboratory tests show that the development model meets the critical functional and performance parameters?                                                                                     |                         |               |                |
| TRL 5                                                                                                    | LIT Prototype                                | (5.1) Were experimental investigations performed in a relevant environment (simulated space)?                                                                                                            |                         |               |                |
|                                                                                                          |                                              | (5.2) Were the critical functional and performance parameters of the components validated in the relevant environment?                                                                                   |                         |               |                |
| TRL 6                                                                                                    | LIT Prototype – complete tests               | (6.1) Was the component demonstrated in a relevant environment (simulated space)?                                                                                                                        |                         |               |                |
| TRL 7                                                                                                    | Client Test – Prototype                      | (7.1) Was the prototype demonstrated in an operational environment?                                                                                                                                      |                         |               |                |
| TRL 8                                                                                                    | Client Test – Pilot                          | (8.1) Was the component qualified in tests and demonstrations in an operational environment?                                                                                                             |                         |               |                |
| TRL 9                                                                                                    | Validation                                   | (9.1) Is the component in operation or has it been successfully operated?                                                                                                                                |                         |               |                |

Note: Elaborated by the authors.

