Maturity Assessment of Critical Technologies

Daiane Rocha
Researcher, daianerocha2505@gmail.com

Gisele Lemes Veiga Araujo
Researcher, araujo.glv@gmail.com

Francisco Cristovão Lourenço de Melo
Professor, francisco.frapi@gmail.com

Aeronautics Institute of Technology – ITA, Praça Marechal Eduardo Gomes,
50 – Vila das Acacias, São José dos Campos – SP, 12228-900 – Brazil

Abstract

A maturity assessment of technological projects is becoming an increasingly popular tool for innovation policy. It enables the accurate determining of risks and opportunities related to the creation of high-tech products. Determining the degree of technology readiness, especially at early stages of development, increases the performance of not only government programs, but also of business projects. This article presents a software interface for such expertise, the IAE/ITA TRL Calculator, designed for the Brazilian aerospace sector. The validation within a number of cases revealed its potential applicability in a wide variety of industries. This innovative software product includes a quality user guide and an improved visual interface that allows for easy and quick identification of issues that require additional effort in order to move the evaluated technology project to a higher level of readiness.

Keywords: innovation; TRL; technology readiness levels; maturity; project management; decision support; TRL Calculator; analysis; evaluation; risk; innovation policy

Citation: Rocha D., Araujo G.L.V., Melo F.C.L. (2022) Maturity Assessment of Critical Technologies. *Foresight and STI Governance*, 16(4), 71–81. DOI: 10.17323/2500-2597.2022.4.71.81

Introduction

Innovation is the basis for economic development (Schumpeter, 1934) and the competitiveness of companies (Porter, 1999). The incentive to innovate in Brazil was tangible more emphatically promoted after 1950 with the creation of CAPES.[1] Although the incentive to foster technological innovation in Brazil began in the 1950s, the country was left out of the space race.

When previously the competition was for nations to reach space, this race currently occurs between different players - private companies. This relevance is confirmed by the high investments from both the government and private sector in search of financial return and positioning of sovereignty and technological independence that the sector provides.

Bryce Space and Technology, which analyzes the space sector, reported that the aerospace industry is currently valued at $360 billion. Bank of America, Space Capital, and Silicon Valley reported that the industry will turn over $1 trillion in the next decade in their prospecting studies.[2]

Although Brazil is not one of the leading countries in the competition, it is the holder of cutting-edge technologies and is improving its innovation indicators, see Figure 1 (Cornell University et al., 2021).

An example of Brazil's progress in innovation and cutting-edge technology was the launching of Amazônia-1, the first Earth observation satellite entirely designed, integrated, tested, and operated by Brazil. Its launch took place on the PSLV-C51 mission of the Indian Space Research Organisation (ISRO) on February 28, 2022.[3]

The mission represented a technological breakthrough and improved innovative development. The improvement in Brazil's innovative development was confirmed by a survey conducted over the last five years (2015-2020) on the innovation indicators of the Global Innovation Index[4] (Figure 1). This survey showed that Brazil has been improving its positions, both in the global index, as well as in the indicators of inputs for innovation (input) and products of innovation (output).

Analyzing the data in Figure 1, we observe that Brazil has been improving its Global Index over the last five years (2015-2020), moving from 70th place to the 62nd, improving eight positions in the overall ranking. This improvement was mainly in the year 2017-2018 and influenced by the improvement of 10 points in the ranking in Innovation Products and two points in Innovation Inputs.

In 2018, research and development (R&D) spending grew by 5.2%, which is significantly more rapid growth than overall GDP growth. That same year Brazil held 10th place among countries with the most global downloads of apps produced by local companies (Cornell University et al., 2018).

Brazil followed in 2019 and 2020 with further improvements in innovation. As shown in Table 1, Brazil's position in the ranking of the General Innovation Index in the Global Innovation Index by subdivision (2015-2020), the positioning score goes from the worst of the last five years as red following to yellow as medium, and the best score with green.

Brazil obtained not only its best placement in the Global Innovation Index ranking for the last five years (2015-2020) in 2020 but also its best positions in the subdivisions of business sophistication, recognition products, and technology and creative outputs, it also obtained relevance in the subdivisions of human capital and research, in which the University of São Paulo (USP) obtained 5th place in recognition among the 10 best ranked universities in middle- or low-income economies.[5]

One factor pulling Brazil's scores upwards are technology companies, universities, and laboratories focused on the aerospace sector. Within the aerospace sector, the technologies are considered complex, so the need for technological development is high (OECD, 2005). These are the technologies called "Critical Technologies (CT)" because they often have military applications and fall within the scope of a country's defenses (Salgado, 2016; Rycroft, Kash, 2002).

In the 1990s, the United States (US) government defined Critical Technology: "a technology is considered critical when it is essential for the US to develop its long-term national security and the country's economic prosperity."[6]

For the Brazilian Institute of Aeronautics and Space (IAE), TCs are: "Technologies necessary for development that are not dependent on the projects and programs established by the Institute." The term "non-dependent" in this context refers to a partial mastery of space technologies, full independence is possible only for the great powers in this area, which have complete space programs (Salgado, 2016)

The development of TCs is a *sine qua non* condition for access to space, providing the countries that have them with "sovereignty and autonomy", in addition to economic factors. They grow an average of 6% per year and yield billions of dollars (Salgado, 2016). Access to space requires highly complex technological development and more complete management, due to the high risk.

In order to reduce the risk, in the 1960s, the National Aeronautics and Space Administration (NASA), the US national aeronautics and space administration agency, developed a metric to assess the level of technological maturity in the development of its technologies, called: Technology Readiness Level, known by its acronym TRL.

[1] Followed by FNDCT, BNDES, and FINEP, created to encourage and finance the propulsion of innovation in Brazil.

[2] https://www.cnbc.com/2022/05/21/space-industry-is-on-its-way-to-1-trillion-in-revenue-by-2040-citi.html, accessed 17.06.2022.

[3] https://www.isro.gov.in/launcher/pslv-c51-amazonia-1, accessed 19.06.2022.

[4] The Global Innovation Index evaluates as indicators of innovation: venture capital, research and development, entrepreneurship, and high-tech production.

[5] https://www.topuniversities.com/university-rankings-articles/latin-american-university-rankings/top-10-universities-latin-america-2020, accessed 15.06.2022

[6] https://clintonwhitehouse3.archives.gov/WH/EOP/OSTP/CTIformatted/AppA/appa.html, accessed 12.03.2022.

The main goal of such a development was to reduce the risk of technology transition from its creation to its use, as shown in Figure 2 (NASA, 2020). Thus, the Technology Readiness Level metric, henceforth TRL, also made it possible to compare different types of technology and their common understanding. The metric consists of measuring the maturity of a technology by demonstrating technological capability and being highly effective in communicating the state of the technology (Mankins, 2009).

The TRL metric currently consists of nine levels that evaluate a technology (Mankins, 2009), the levels range from basic research to experimental development to technology, i.e., it is considered an R&D (research and development) metric.

The GAO (US Government Accounting Office (USA)) uses the TRL metric to define projects to be developed and does not use technologies with a TRL less than 6 in its projects. The European Commission in its Horizon Europe research program has also used the metric in defining investment estimates in selected projects.[7] In Brazil, Embrapii, in a government action to promote innovation, used a minimum cut-off for TRL of 3 for its projects.[8]

There are numerous adaptations today regarding the application of the TRL metric. In the US, there are four institutions that use the metric in different forms: the calculator developed by the US Air Force Research Laboratory[9], called the TRL Calculator; which is already in its second version; the guidance developed by the Department of Defense (DoD, United States Department of Defense)[10]; the NASA checklist; and the GAO checklist.[11] The European Space Agency (ESA) has a Handbook describing their way of applying the metrics (ESA, 2008). In short, the application process has been adapted and specified according to the characteristics of each institution.

In Brazil, funding institutions and research institutes[12] use the TRL metric as a prerequisite for project submission and project controls to define the current status of the project and the set goal.

In Brazil, in addition to the natural challenge of space technologies due to the high risks and lack of technical knowledge, the biggest challenges inhibiting the development of space activity are two: human and financial resources.[13] Thus, Brazil aims to differentiate itself from the world's great aerospace leaders. Given the reality of the Brazilian aerospace context, there was a need to adapt the TRL metric to the country's reality.

Technology Readiness Level

The TRL metric was developed by NASA in the 1960s. Initially, there were seven levels that differentiated and defined technological maturity, in the 1990s the metric was revised and it was found that two more levels were needed bring the total to the current nine levels of technological maturity. In the same decade, a definition of each of these levels was published (Mankins, 2009).

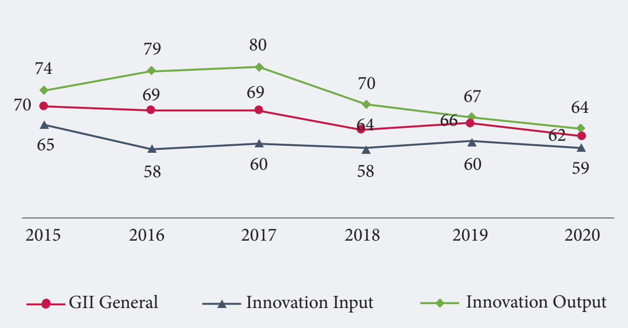
Due to the popularity of the metric and the superficial definition of each level, a large number of institutions and sectors have adapted the TRL metric. The popularity and validation of the metric's relevance was confirmed with a bibliometric analysis that allowed for identifying the growing number of publications using the metric in technological projects (Araujo, 2020).

The bibliometric analysis took place on the Web of Science database, "Technology Readiness Level" OR "Technology Readiness Levels" in the technology domain: "Main Collection"; the survey was based on a timeline from 1991 to 2021 (as shown in Figure 2). The cutoff at the beginning of the analysis in the 1990s was due to the date of the first publication explaining the then nine levels of technology maturity.

There were 1,103 published papers that used TRL, conducted by 71 different countries, the most relevant being the US with 39% of all publications, followed by the UK and Germany with 12% and 11%, respectively. The publications were identified in 124 different categories, with 53% of the publications in the engineering field and 19% of them with a specific application in aerospace engineering.

As shown in Figure 3, there is a spread of metrics and an increase in the number of publications in the 2010s due to the ISO Standard that was released in 2013. ISO 16: 290: 2013 Space Systems - Definition of the Technology Readiness Levels (TRLs) and their criteria of assessment (later translated by ABNT NBR ISO 16: 290:

Figure 1. **Position of Brazil in the Global Innovation Index ranking (2015-2020)**



Source: authors, using GII data.

7 https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf, accessed 19.02.2022.

8 https://embrapii.org.br/wp-content/images/2020/08/MINUTA-RELATO%CC%81RIO-ANUAL-2019-EMBRAPII-Vers%C3%A3o-Final-SAF-L1_revisado.pdf, accessed 07.03.2022.

9 http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104463/air-force-research-laboratory.aspx, accessed 06.06.2022.

10 https://www.researchgate.net/file.PostFileLoader.html?id=5566cff45cd9e318e88b4696&assetKey=AS:273785192681472@1442286884102, accessed 11.01.2022

11 https://www.gao.gov/assets/gao-20-48g.pdf, accessed 04.01.2022.

12 Such as Embrapa, INPE, UFAN, PROFNIT, as well as AEB-Brazilian Space Agency.

13 https://www.gov.br/aeb/pt-br/centrais-de-conteudo/publicacoes/institucional/PNAEPortugues.pdf, accessed 06.06.2022.

Table 1. **Position of Brazil in the ranking of the General Innovation Index in the Global Innovation Index by subdivision (2015-2020)**

Subdivisions	Years					
	2015	2016	2017	2018	2019	2020
General Ranking	70	69	69	64	66	62
Institutions	85	78	91	82	80	82
Human Capital and Research	63	60	50	52	48	49
Infrastructure	67	59	57	64	64	61
Market Sophistication	87	57	74	82	84	91
Business Sophistication	37	39	43	38	40	35
Knowledge and Technology Outputs	72	67	85	64	58	56
Creative Outputs	82	90	83	78	82	77

Source: Authors. Data collected from the Global Innovation Index (2015-2020).

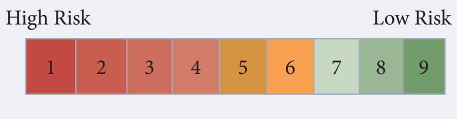
2015 Space systems - Definition of Technology Maturity Levels (TRLs) and their assessment criteria): "This Standard defines Technology Maturity Levels (TRLs). It is primarily applicable to materials related to space systems, although the definitions can in many cases be used in a wider domain."[14]

By performing the forecast (Figure 4), one can identify an even more impressive growth in the number of publications and implementations in the following years.

The standard was created to focus on the aerospace sector and focused primarily on software, as described therein. Olechowski et al. (2015) detects some of the greatest flaws found in ISO 16290: 2013, however, the benefits of the metrics are greater (Dawson, 2007) (Table 2). The TRL metric assists in the management of technology projects. Its relevance is indicated by the NAP, which stresses the importance of industrial advancement in the space sector (Salgado, 2016).

GAO published a study on their projects using only technologies with a TRL above 6 against projects with any levels of TRL for the technologies (Sullivan, 2007). The result was that in projects with a TRL above 6, there was no schedule delay and no budget growth forecast, while in projects using a TRL below 6, there was up to a 120% schedule delay and a 101% budget growth.

Figure 2. **Level of risk for technology transition**



Source: authors, using (NASA, 2020).

Its relevance is also proven by the aerospace institutions that have been using and adapting the standard to the reality they are experiencing. Among them are those mentioned above: NASA, ESA, AFRL, and DOD, as well as JAXA (Japan Aerospace Exploration Agency), MCTI (Ministry of Science, Technology and Innovation), INPE (National Institute for Space Research), and the Brazilian Armed Forces. In addition there are private sector companies that employ this standard such as: ALSTON, Google, Embraer, Raytheon, and others (Rocha, 2016).

Materials and Methods

The authors want to mitigate the shortcomings of applying the metric using only the parameters of ISO 16290: 2013 and are motivated by the intention to make the application of the TRL metric feasible and easy. The stipulated parameters were not only addressed by NBR ISO 16290: 2015 but also by added views on economic, political-legal, technical, and knowledge management feasibility.

The first version of the calculator was based on applications from the following institutions: NASA, ESA, DOD, and AFRL, as well as the checklist described in ISO 16290: 2013. After its development, the TRL calculator received recognition for its importance and ease of use by some Brazilian institutes for development[15] and it has more than 20 applications made by IAE researchers.[16]

Along with the recognition and popularity of the TRL Calculator, opportunities for improvement were identified. Among them:

- Differentiation in the weights of the analyzed areas.
- Bias in questions marked as ISO.
- Lack of clarity regarding improvement with only a visualization of the result in the dashboard.
- Difficulty in understanding some of the questions.
- Difficulty in applying it to technologies outside the aerospace sector.

Aerospace institutions already apply TRL and have publications with some differences in the application of the metric (Rocha, 2016). The differences were analyzed for the construction of the first version of the Calculator and maintained for the current version, with an update only in the fifth part of the TRL application process. The five analyzed application parameters are presented at Table 3.

The IAE/ITA TRL Calculator

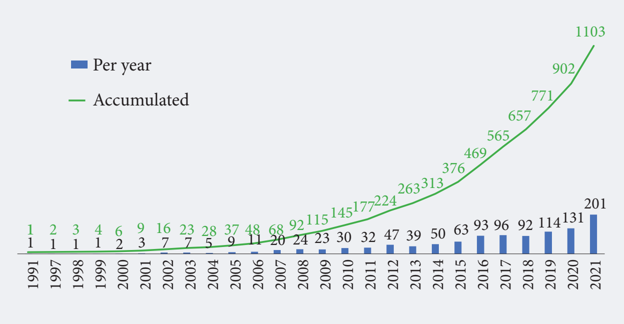
The IAE/ITA TRL Calculator is a tool that assists with the assessment of TRL that is now in its second version. The calculator assists in the fifth step of the assessment process. The TRL metrics are included in the tool provided in Microsoft Excel software. During the evalu-

[14] https://www.target.com.br/produtos/normas-tecnicas/43781/nbriso16290-sistemas-espaciais-definicao-dos-niveis-de-maturidade-da-tecnologia-trl-e-de-seus-criterios-de-avaliacao, accessed 06.06.2022.

[15] Among them are ABDI - Brazilian Agency of Industrial Development , IAE- Institute of Aeronautics and Space, Brazilian Space Agency, PROFNIT.

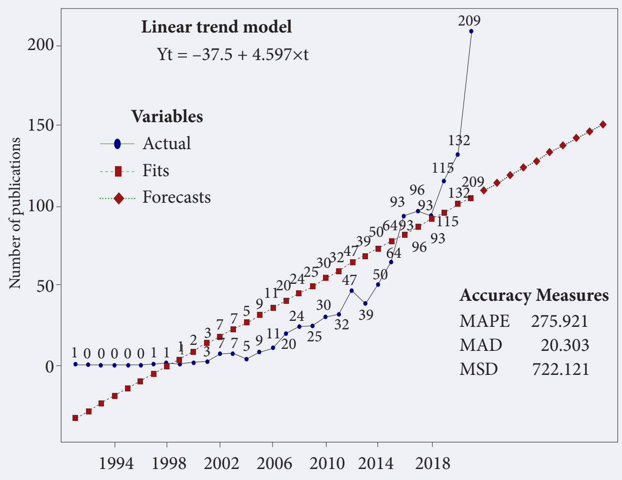
[16] https://iae.dcta.mil.br/index.php/calculadoras-trl-e-mrl, accessed 06.06.2022.

Figure 3. **Dynamics of growth for TRL-related publications, by year of publication**



Source: authors, using (Salgado, 2016).

Figure 4. **Forecasts for growths of TRL-related publication flows**



Source: authors.

ation stage, technical, economic, political-legal, and documentary aspects were included in addition to the framework issues of NBR ISO 16290: 2015.

The demonstration of the TRL evaluation methodology consists of standardizing knowledge about the TRL methodology, using the Calculator created in Microsoft Excel software with the TRL concept used for standardization:

"TRL is a demonstration tool that assesses the maturity of a technology, product or project. It helps decision makers to get an accurate result. Helps keep projects within a predetermined cost, time and effort. Provides stakeholders with a common understanding of managers, technicians and researchers. Defines the status of the technology, facilitating feedbacks, technology comparisons, and future decision making."[17]

The process of applying the TRL assessment using the Calculator occurs in four steps, they are:

1. The methodology demonstration process is the process in which the facilitator seeks to standardize the knowledge of the TRL indices for the assessment respondents, instilling everyone with a minimum knowledge of the levels and the prerequisites for the levels, as well as explaining the assessment concept and its benefits.
2. Technology data consists in identifying and framing the technology to be evaluated.
3. The technology weights consist of the consideration of the weights per criterion to be evaluated.
4. The maturity evaluation consists of a questionnaire to be answered and a checklist to be performed of the materials collected.

The first step, for demonstration purposes, has as an aid the first part of the Calculator that has access to the basic criteria of the NBR ISO Standard and a Manual that explains how to use this tool, and the start button that takes the responder to the second step (Figure 5).

The content of the Handbook (Figure 6) consists of an explanation of the background of the TRL, followed by an explanation of the use of the application in Microsoft Excel, as well as an explanation of the calculations performed to obtain the result. Furthermore, it includes an explanation of how to read the result obtained with the Calculator.

We also have checklist criteria withdrawn from the ABNT NBR ISO 16290:2015 Standard (Figure 6). It contains three columns: 1. The definition of each level of technological maturity, 2. The framework achieved for each level or what needs to be done for the completion of each level, and 3. The necessary documentation for each level.

Clicking the start button shown in Figure 5 will open the second step (Figure 7) that consists of answering questions about the technology data. All answers in this part consist of collecting data for documentation pur-

Table 2. **Benefits and Flaws of TRL metrics**

Flaws (Olechowski et al., 2015)	Benefits (Dawson, 2007)
• It does not evaluate know-how, only documentary data; • It does not evaluate the means of knowledge transfer; • Does not address political legal aspects; • It does not standardize the evaluation; • Does not address economic and documentary aspects; • It does not perform quantitative analysis.	• Ease of common understanding about the current state of technology for a given application; • Comparison of technologies in their current phases (snapshot); • Risk management; • Decision making related to technology financing; • Decision making related to technology transition; • Metric assessment of the maturity of the project›s technologies program, before development begins.
Source: authors, based on the abovementioned works.	

[17] https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

Table 3. **Analyzed application parameters**	
Parameter	**Description**
1. Application Decision	It must be carried out via the evaluation process call, and can take two forms: pre-established frequency, or only when something changes in the project or technology, according to GUIDANCE, ESA
2. Term Definition	Presence of the facilitator, person responsible for the application of the metrics and conference (documentary audit) (FERENCE, 2012), in addition to the researcher, knowledgeable of the evaluated technology, the manager responsible for the development mission and the knowledgeable of the operational environment (NBR ISO 16290, 2013).
3. Identification of technologies	The evaluation must be carried out on all technologies, complete model; in the case of up grade only associated technologies (NASA, 2007).
4. Collecting materials	The assessment must be carried out by means of a documentary checklist, as described in NBR ISO 16290: 2015. The audit process must be carried out together with the technology development team.
5. Evaluation	The TRL assessment takes place in 3 steps: a) demonstration of the TRL assessment methodology (consists of standardizing the knowledge of what is TRL for all respondents to the assessment); b) data of the technology to be evaluated (identification and framework of the technology to be assessed - the framework may be research and development; construction of the technology and validation and production); c) TRL evaluation (questionnaire to be answered and checklist performed to complete the achieved TRL).
Source: authors.	

poses, i.e., they have no influence upon the maturity assessment calculations.

These are the name of the technology, the current respondent, and the date of the assessment. It is necessary to digitalize these fields. The other questions to be answered consist only in selecting in which field the evaluated technology fits, these prompts include the type of technology and the application of the technology.

The type of technology to be evaluated is the definition of whether a technology is hardware or software. The intended status consists of saying which status you want the technology to reach and there are three statuses: research and development, technology construction, and validation and production, which are explained in Table 4. Further, the technology application can be classified as infrastructure, distribution, or application. Infrastructure technologies are technologies considered disruptive or basic. They are the bases of technological development, the technologies that will be allocated to a vehicle or satellite. Distribution technologies are the technologies that allow the application technologies to exist, they are middle technologies. Finally application technologies are the technologies that go to the final consumer.

Clicking the START EVALUATION button will open the third stage of the Technology Data evaluation, the stage where you will indicate the weights for each of the aspects included in the evaluation, Figure 8.

As weights, there is the possibility of including five levels for each of the criteria, according to the Likert scale, which is a scale for questionnaires, widely used for questions with a higher level of nuances than a yes or no answer and is great for delving into a specific theme and finding out more detail. The weights were stipulated by the degree of importance with the respondent being able to place maximum importance on all of them or none of them.

There are five criteria, which are evaluated: the NBR ISO 16290:2015 Standard; the technical knowledge criterion of technology development; the economic criterion of feasibility and the economic potential of the technology; the political-legal criterion of feasibility and potential for technological development and technological commercialization; and lastly the documentary criterion of the security of knowledge management for the developed technology. The weights are defined through a Likert scale, which defines five levels of importance: 1- Not important; 2- Not very important; 3- Moderately important; 4- Important and 5- Very important. The weights impact TRL calculations.

After choosing the weights that best fit the technological development profile, the respondent must mark the degree of tolerance accepted for level compliance. It is worth mentioning that the AFRL uses an 85% level for the fulfillment of development as approval to move on to the analysis of the next level, accepting a 15% tolerance of non-compliance with the requirements.[18] The AFRL seeks to develop technologies up to TRL 6, then transfer the activities to the development sector. The degree of tolerance will be stipulated by the respondent.

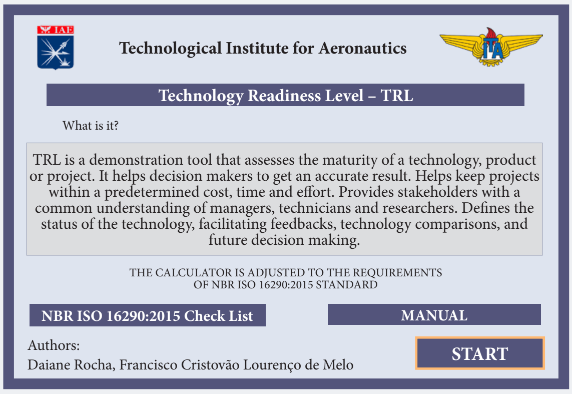
The tolerance calculation is based on the groups, all respondent questions of TRL 1 add up to 100%. If the tolerance is 85%, the respondent may not meet 100% of any of the questions, within the 85% threshold, if non-compliance is greater than the tolerance, it will result in the TRL value.

After setting the tolerance level, the respondent clicks the START ASSESSMENT button , and will be transferred to the questions page (Figure 9).

This screen contains the name of the evaluated technology, the name of the respondent, and the evaluation date. The questionnaire is divided by nine TRL level blocks and these blocks contain questions that fall under the five criteria (NBR ISO 16290:2015, technical, economic, political-legal, and documentary), however the respondent will not have visibility. There are questions that fit more than one criterion and will be counted for both criteria (Table 7). The respondent can select how much they have already fulfilled the question in the prompt, with the answer ranging from 0 to 100 in multiples of 5 (to change the value, simply select the arrows on the

[18] https://apps.dtic.mil/sti/pdfs/ADA411872.pdf, accessed 07.02.2022.

Figure 5. **IAE-ITA-2021-1 Maturity Calculator Home Page**



Source: https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

Table 4. **Technology Status**

TRL Level	TRL Group	TRL Group Description
1–3	Research and Development (R & D)	Research and technology exploration activities, discovery and formulation of the technology concept to be developed.
4–6	Technology Construction	Development of the technology and application concept (prototype), experimental testing of the technology carried out in a relevant laboratory environment.
7–9	Validation and Production	Demonstration in aerospace, qualified system and mission achieved, possibility of scale reproduction, partnership process and technology transfer to industry.

Source: authors, using (NASA, 2020).

drop down menu of values present at the beginning of each question).

After filling in the complete questionnaire (113 questions), a comparison of the results is possible. The comparison can only be made with questions from NBR ISO 16290: 2015 and the total score for the questions is developed by added criteria. The result is a dashboard that aims to handle the questionnaire data and explain in a clear and intuitive way the gap in the development of the technology for advancement to the next level through a radar graph (Figure 10).

To construct the radar, the Delta TRL was used. In 2002, Mankins presented the definition of the Delta TRL as the difference between the current level of maturity of a given technology and the desired level of TRL for a given point in the future

(Δ TRL = TRL Desired - TRL Actual). This is because, each stage represents another level of maturity in the development, therefore, more stages would typically be equivalent to the highest level of uncertainty in R&D over a given period of time (Mankins, 2002).

The importance of this analysis lies in the relationship between the increased level of TRL and the increased costs of technological development projects. Two factors that have a direct influence upon the development schedule (Araujo, 2020).

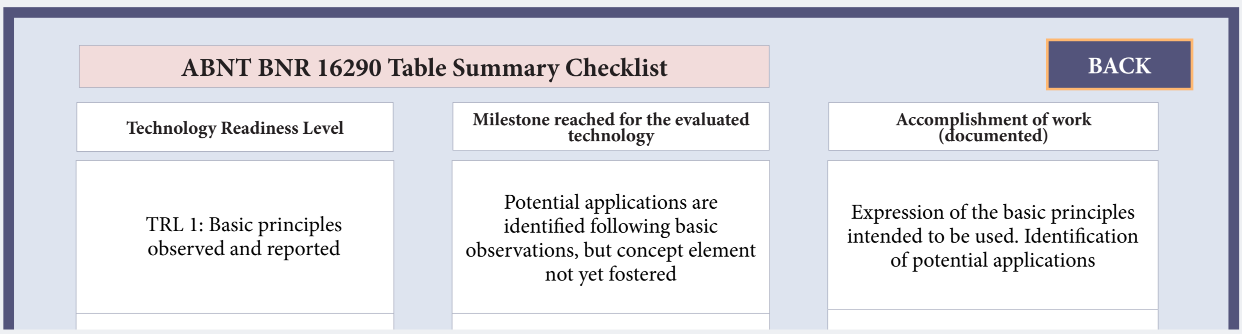
The application for the validation of the developed methodology took place in four technologies of the aerospace sector. The technologies were chosen to comparatively analyze the following aspects:

- Application in different sectors: one defense technology, MARIMBA, and three space technologies: Carbon Fiber-Reinforced Thermoplastic Composites, L75 Engine, and VSB 30.
- The completed projects (MARIMBA and VSB 30) and ongoing projects (carbon fiber reinforced thermo-structural composites and L75 engine); and
- Technologies with a systemic view (VSB 30, L75 Engine, and MARIMBA) and basic technology (carbon fiber reinforced thermo-structural composites).

Table 5 provides a brief description of the technologies that were evaluated:

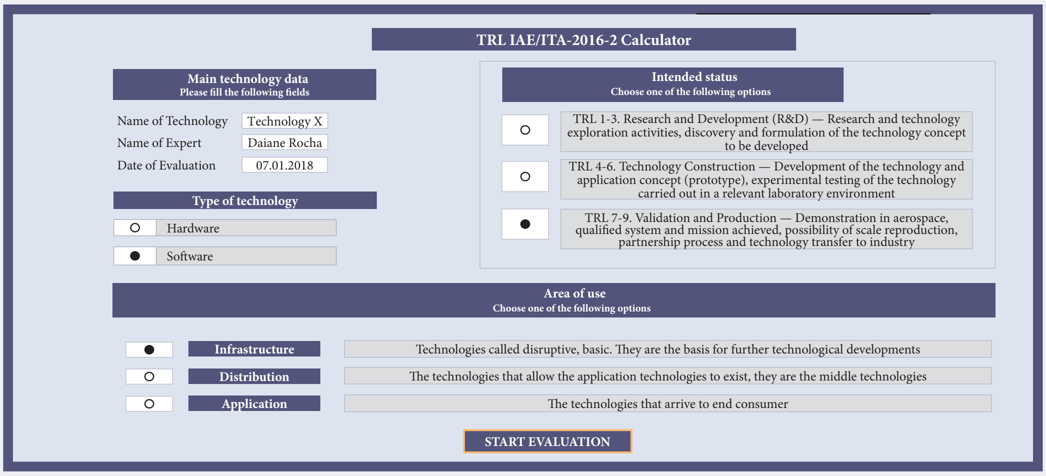
The evaluation process took place through interviews with experts lasting approximately two hours. The application of the methodology followed the five steps mentioned above. The application was done using the second version of the TRL IAE/ITA Calculator tool for the evaluation. The weights were all set to the same value.

Figure 6. **Query the requirements of the standard (Adapted from NBR ISO 16290, 2015)**



Source: https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

Figure 7. **Technology Data**



Source: https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

Results

In three of the four evaluations performed, the NBR ISO 16290: 2015 Standard obtained a more advanced TRL than the TRL with requirements created for the Calculator. In addition, the VSB 30 technology obtained the maximum TRL in both evaluations.

Besides the VSB 30 technology, which proved to be neutral in representing the subjectivity of the NBR ISO 16290: 2015 Standard, the other evaluated technologies confirmed the raised aspects of modifications of the first version and demonstrated subjectivity in 75% of the evaluations.

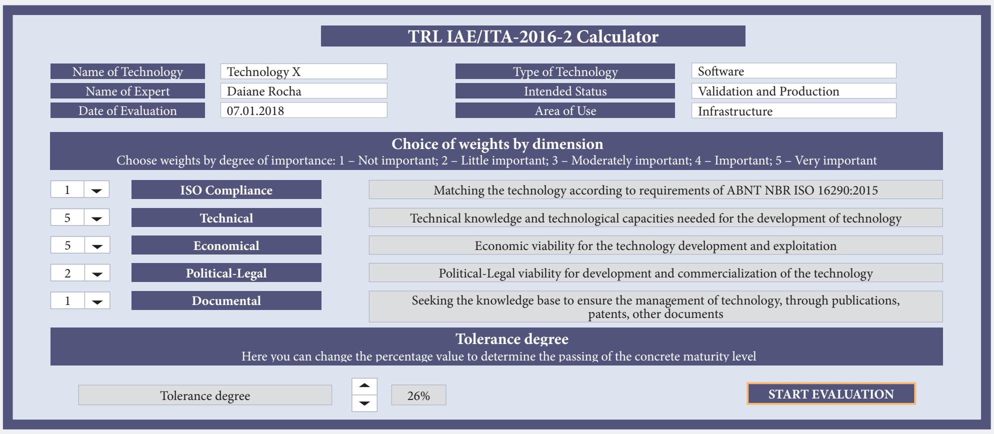
The relevance of including the added aspects was confirmed by the interviewed researchers and managers. The documentary concern mitigates knowledge transfer, since all steps and know-how for technological development are documented. The transfer to industry added in the last TRL proved to be relevant for possible production at scale, the inclusion of economic issues, and the development of a business plan makes this transfer feasible.

The inclusion of political and legal aspects for embargo issues proved relevant for enabling development. The use of quantitative and qualitative data allows the manager to make a detailed assessment of the aspects of project development and makes strategic decision making possible. The evaluation process developed a standardization of the evaluation, helping in a comparison of similar technologies and technologies used in different projects, apart from the comparison between projects.

The dashboard visualization of the results proved useful for the interviewees and the data was easy to understand, showing the points that need to be improved to obtain the next maturity level.

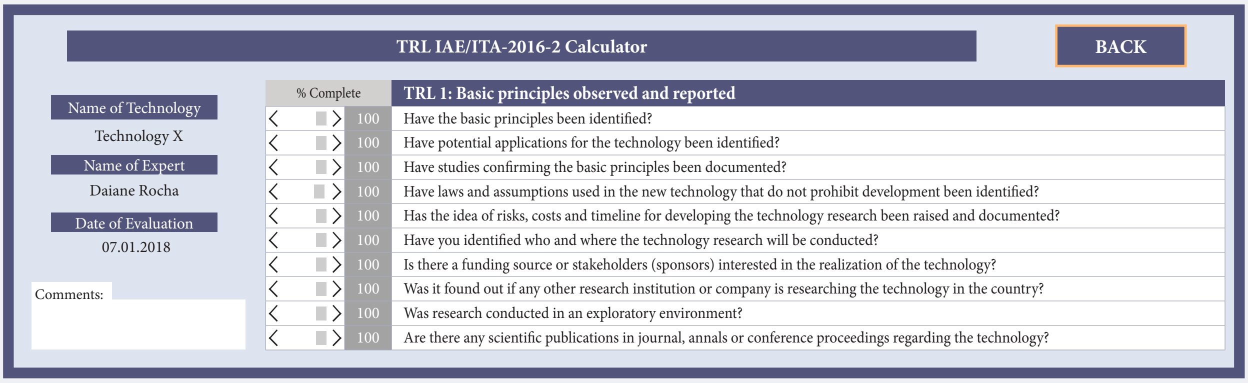
In order to validate the application of the metric used in the IAE/ITA TRL Calculator tool and the inclusion of Delta TRL, the present work used four projects in the area of propulsion that had already been evaluated by Salgado (2016). These technologies were identified by the IAE as technologies considered critical and the institute aims for their development and a comparison of the results (Salgado, 2016). These projects were: C/C Can-

Figure 8. **Technology Weights**



Source: https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

Figure 9. **Technology Maturity Evaluation**



Source: https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

yon Tubing (Garganta de Tubeira C/C), Turbopump (Turbobomba), Combustion Chamber (Câmara de Combustão), and the Liquid Propulsive Stage (Estágio Propulsivo Líquido).

The construction of a roadmap by Salgado (2016) was conducted through workshops, involving opinion polls, with researchers from the areas involved in 2014. Thus, a methodology was not used to guide the maturity analysis (TRL) of the technologies under development. For this reason, four projects were selected for the application of the TRL metric through the Rocha, 2016 methodology and with the second version of the IAE / ITA TRL Calculator, which considers national and specific criteria for the aerospace sector and the ABNT NBR ISO 16290: 2015 standard.

Below, in Table 6, are presented the results of the TRL analysis of the four projects in the propulsion area, which were compared with the data obtained by Salgado (2016).

With the TRL results presented for the projects analyzed here, it was possible to apply TRL Δ. Thus, one can see in Table 7 the TRL Δ found for each project.

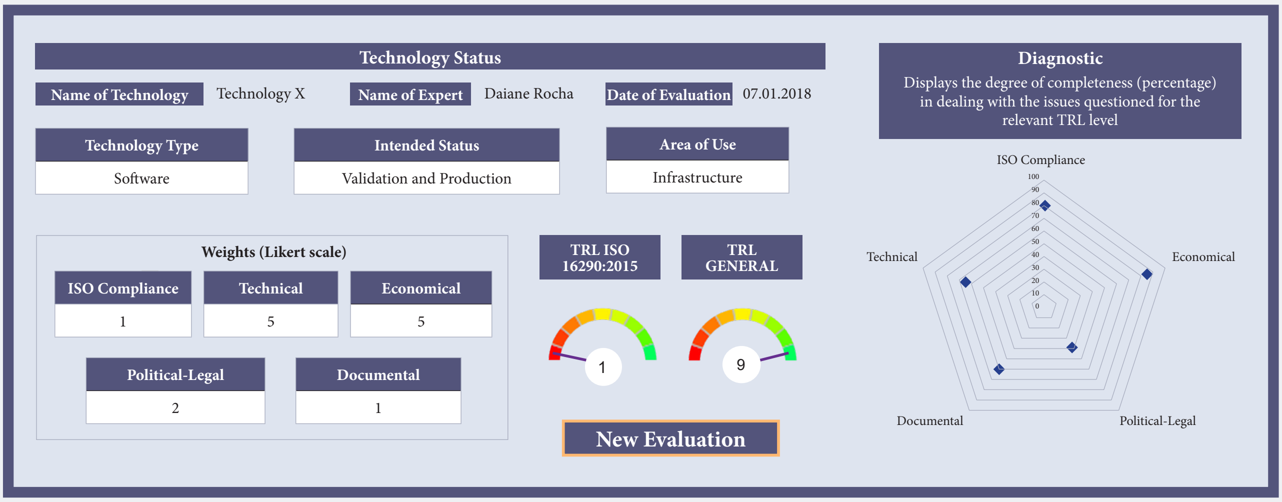
Discussion

Technology maturity levels (TRL) provide a common understanding of the state of technology development. The assessment of technology maturity using the metrics occurs based on the state of progress of each technology. The benefits of using TRLs are related to better communication, results, and management of a research program (Araujo, 2020).

When comparing with the data obtained by Salgado (2016), through workshops and a reference table, we found that at the time, without the use of a TRL level analysis tool, the Garganta de Tubeira C/C project was classified as TRL 5, but when we applied the second version of the IAE/ITA TRL Calculator tool, the project showed a TRL 1 level.

Next, the Turbobomba and Câmara de Combustão projects, which are subsystems of the L75 MFPL and were being developed together, were analyzed. Both projects demonstrated TRL 4 and IAE/ITA TRL 4 according to NBR ISO 16290: 2015. When analyzing the results obtained by (Salgado, 2016), we found that both projects were from TRL 2 to TRL 4.

Figure 10. **Technology Status**



Source: https://iae.dcta.mil.br/images/Calculadora_MRL_e_TRL/CalculadoraTRLIAEITA2020.xlsm, accessed 12.06.2022 (in Portuguese).

Table 5. **Evaluated technologies**

Technology	Description
1. MARIMBA	IAE project in the Materials / Defense sector, researched for 11 years, concluded in 2011. The project developed materials resistant to ballistic impact, for use in aircraft, helicopters and military vehicles. According to the project manager in an interview to evaluate this technology in TRL IAE / ITA-2016-1 Calculator, the technology targets TRL 9, but the process of transfer to industry has not been completed due to bureaucratic problems.
2. CARBON	Consists of thermostructural carbon composites reinforced with carbon fibers using hydroclavens. The simple compaction of reinforcing fibers, natural or synthetic, agglomerated with a binder material in the form of a thermosetting resin formulated with hardeners, forms lightweight materials structurally suitable for a variety of applications, bringing benefits to various industrial segments ranging from medical to aerospace.
3. L75	Consists of the design, manufacturing, testing and operation of a liquid rocket propulsion engine (liquid oxygen and kerosene). Technology of interest to the country described in the NAP, which aims to train it in the area of liquid propulsion, aiming to increase the capacity of launch vehicles to compete in the international space transportation market. In an interview to evaluate this technology in TRL IAE / ITA-2016-1 Calculator, the manager responsible for the technology aims to develop the prototype of the technology that is still in laboratory tests and in the research process, and aims to achieve TRL 5.
4. VSB-30	A sounding rocket, the result of a partnership between the IAE Institute and the German Aerospace Center (DLR) that funded part of its development. It is a certified vehicle. The qualification process for the rocket was evaluated by the European Space Agency (ESA), the DLR and the Swedish Space Agency (SSC), as well as the companies Kayser-Threde and EADS. The rocket has had seven successful launches: two in Brazil and five in Sweden. The VSB-30 aims at the transfer to the industry, since it is necessary and of political interest for scale production and to enable investments for the industry, since it is a certified product, with quality assurance. The certification consolidates VSB-30 as the best product in its category and one of the few in the world with a formal quality guarantee, issued by an internationally recognized competence body,» says the director of the Institute of Aeronautics and Space (IAE), Colonel Francisco Carlos Melo Pantoja. The delivery of the homologation certificate by the CTA's Industrial Promotion and Coordination Institute (IFI), according to Pantoja, also accelerates the process of transferring the vehicle's production technology to the Brazilian industry. Currently, several companies are working on its development and production: Villares, Cenic, Fibraforte, Mectron, Compsis, Avibrás, Orbital, among others.

Source: authors.

The analysis of the Net Propulsive Phase project resulted in TRL IAE/ITA - 2016 level 1 and TRL 2 according to NBR ISO 16290: 2015. In the analysis performed previously by Salgado (2016), such project had demonstrated TRL 2.

Through the results presented it is possible to verify that the use of the IAE/ITA TRL calculator tool, in addition to facilitating the application of the methodology, also makes the verification of the TRL levels of projects more accurate, especially when dealing with projects with low TRL levels.

The data collected by Salgado (2016) was obtained in 2014, while the TRL levels of the same projects using the tool were obtained in 2018. In the time interval between the completion of the two studies, we found that of the four projects analyzed here, only two managed to raise the TRL level: the Turbobomba and Câmara de Combustão projects, both of which grew two TRL levels in the period.

During the analyses, the commitment of project management to find budget sources and partnerships in order to meet the project schedule became clear, which likely contributed to the two-level increase of the TRL of these projects.

Regarding the Garganta de Tubeira C/C project, it was reported during the interview with the researcher that the stagnation of the project occurred due to a lack of partnerships with companies to realize the prototype, since the DCTA does not have the infrastructure for its construction.

Regarding the Estágio Propulsivo Líquido project, it was reported that the Turbobomba and Câmara de Combustão projects are being prioritized to later focus on the development of the Estágio Propulsivo Líquido project.

Conducting the adaptation mitigated the issues raised in the research questions with the inclusion of questions pertinent to technological, economic, documentary, and political-legal issues. The evaluation process standardized, made feasible, and streamlined the evaluation process with the application given in Microsoft Excel. The validation of the methodology performed on the four technologies allowed us to analyze and adapt the methodology to the different contexts of the space and defense sector, with completed and ongoing projects and technologies with a systemic vision and basic technology. This research achieved its goal of expanding the knowledge of TRL and providing an adaptation in the process of evaluating TRL in technologies.

Conclusion

Due to the applications of the first version of the Calculator and the identification of the five points to be improved upon, the second version of the Calculator

Table 6. **TRL analysis of the studied projects**

Project	TRL NBR ISO 16290:2015	TRL NBR IAE/ITA – 2016-1 Calculator	TRL (Salgado, 2016)
«Garganta de Tubeira C/C»	3	1	5
«Turbobomba»	4	4	2
«Câmara de Combustão»	4	4	2
«Estágio Propulsivo Líquido»	2	1	2«

Source: authors.

Table 7. **ΔTRL analysis of the studied projects**

Project	TRL_{Actual}	$TRL_{Desired}$	Δ TRL
«Garganta de Tubeira C/C»	1	5	4
«Turbobomba»	4	7	3
«Câmara de Combustão»	4	7	3
«Estágio Propulsivo Líquido»	1	7	6
Source: authors.			

was created. The identified points of improvement were treated as follows:

Differentiation in the weights of the analyzed areas. All areas and all evaluation questions had the same weight in the TRL calculation for the first version. In the present version, it is possible for the respondent to put different weights on each area (Political-Legal, Technical, Documentary, Economic, and ISO). The weights are defined through a Likert scale, which defines five degrees of importance: 1 - Not important; 2 - Not very important; 3 - Moderately important; 4 – Important; and 5 - Very important. The weights impact the TRL calculations.

Bias in questions marked as ISO. In the previous version, the respondent could identify questions that counted towards the ISO Standard evaluation and questions that did not impact ISO. In the present version, the respondent is unable to identify which questions are or are not relevant to ISO.

Lack of clarity describing improvement and only containing a visualization of the result on the dashboard. There was an improvement process in the dashboard visualization of the final result, the inclusion of the radar chart with the Delta TRL proved to be of great importance because the respondent can identify which area he needs to improve upon and demand more effort to obtain the next maturity level.

Difficulty in understanding some of the questions. The inclusion of a glossary for a better understanding of the questions in the manual proved to be very important for the respondents.

Difficulty when applying to technologies outside the aerospace sector. The generalization of the aerospace nomenclatures in the questions, the adaptation and inclusion of new questions, as well as a greater focus on becoming a project management tool made the tool's questions easier to understand and more applicable to other sectors.

Ultimately the tool, along with the application process, proved useful and replicable. The search for such a tool by government agencies and research institutions reinforces the need and feasibility of such a tool for this author. In Brazil, the maturity assessment is being requested at governmental agencies to incentivize and encourage research.

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