Technology Audit: Results of the Assessment of the Technological Maturity of Brazilian Innovation Institutes

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Abstract: The *technology audit* enables the assessment of the technological capability and thus the technological maturity of an RTO. It focuses on the analysis of the research activities in the R&D service areas of the RTO. This allows for a comprehensive understanding of the technologies used, the research competencies, the technologies developed, and the established technology partnerships of the RTO. Since 2017, technology audits have been conducted to evaluate the technological maturity of Brazilian SENAI innovation institutes (ISI). In the last seven years, 41 audits have been completed, providing ample opportunity to extensively test and refine the methodology. As experts 46 technology auditors from 17 different institutions participated. The extended duration and involvement of numerous experts facilitated continuous improvement of the methodology, necessary processes, and roles as well as needed materials. Two rounds of technology audits were conducted between 2017 and 2023. In the first round until the end of 2019, all 23 operational ISIs were audited, with 15 undergoing re-audits in the second round by the end of 2023. In this paper, the results of the application of the technology audit to assess the technological maturity of Brazilian Innovation Institutes is described. The objective of this evaluation of the application, which this paper undertakes, is to exemplify and verify the methodology of the technology audit. To this end, the background of 26 Brazilian SENAI innovation institutes is outlined to contextualize the use of the technology audit in these RTOs. Subsequently, aggregated results from 41 conducted technology audits are described, and concluding implications for the method are derived.

Keywords: Technology audit, Technological maturity, Technology assessment, Technological capability, Technological resources, Technological competences, Technology evaluation, Strategic technology management, Research and technology organizations

1. Introduction

Around the world, developed nations have found a way to strengthen their national innovation ecosystems over time with a variety of complementary entities playing important roles together, in order to foster economic growth. Among those players, RTOs (Research and Technology Organizations) have taken a very important role of creating bridges among those entities that create knowledge (e.g. universities), those entities that apply knowledge to innovate (e.g. companies) and those entities interested in promoting the efficient use of knowledge for impacting societal and economic development (e.g. governments). (Hecklau et al. 2020)

For accomplishing that difficult intermediation role, RTOs must learn and professionalize their businesses to integrate and deal with scientific discoveries and developments from universities, translate such knowledge into viable applications for client companies, and sensibilize government and decision-makers about important and strategic business opportunities, interpreting their impact on society and economy. Therefore, the proper strategic positioning and execution of such a role in the innovation ecosystem requires continuous development of technological and management competences by multidisciplinary teams, as well as deep networking capabilities with partners and clients. (BMBF 2022; Arnold et al. 2010; Breznik 2015; Kröll 2007; Figueiredo 2014; Zehnder 1997)

Within the Brazilian innovation ecosystem, SENAI decided in 2012 to launch an ambitious program for fostering the increase of national industrial competitiveness, by planning and implementing new RTO structures under its broad set of unities spread all over Brazil. Since its creation in 1942, as a private entity guided by industry, but with non-profit orientation, SENAI has always served the Brazilian industry with high quality technical and technological educational services. The extension to further technological businesses (e.g. metrology and consultancy services) came along time (around the 80s) with the industrial need for precise quality control in production environments. With the development of global innovation chains and strategies in this new century, it was time for SENAI to also expand its portfolio of "applied technological services" to the Brazilian industry with dedicated applied research centers, thus creating the SENAI Innovation Institutes (ISI) in direct cooperation and governance with CNI (National Confederation of Industry), with the Brazilian government and supported by investments from BNDES (National Development Bank).

The initial creation of 26 new applied research institutes by SENAI in 2012 had a deep inspiration in the well-known German Fraunhofer model and counted with the direct partnership of Fraunhofer IPK for such a challenging implementation. This successful partnership supported the expansion of the network to 27 current operating SENAI Innovation Institutes, which are guided and frequently evaluated with global best practices for R&D management. Among such practices, technology audits have been structured, conducted and evolved over time, in order to assess the technological capabilities of SENAI innovation institutes from the point of view from external experts, who are regularly dealing with, or have already become known global references in their technological fields. (Kohl et al. 2020; Kohl et al. 2015)

This paper intends to provide further information on the methodology behind such technology audits, as well as the results and impact for SENAI over time with its application among its innovation institutes as a guiding instrument for continuous improvement within a challenging and dynamic innovation ecosystem. For this purpose, a methodological approach was chosen that focuses on the description of the theoretical orientation and the extensive practical application of the technology audit as well as on a comparative analysis of the quantitative results. The research contribution of the paper lies in transparently documenting the development of a fit-for-purpose and application-oriented method for the technological assessment of RTOs and testing its suitability in application in order to improve the method based on the research results.

2. Technology Audit for Research and Technology Organizations

The Technology Audit represents a systematic methodology designed to analyze and evaluate the technological maturity of Research and Technology Organizations (RTOs), identifying opportunities for enhancement and initiating optimization processes. This audit employs a standardized procedure incorporating various models, such as the maturity model and assessment dimension model, alongside tools and templates, to facilitate a structured evaluation of the RTO being audited. (Hecklau et al. 2022b)

To obtain the necessary insights for assessing the technological maturity, all technological areas within the RTO are examined. A targeted approach involves selecting and discussing specific, representative research activities conducted in these areas. This approach provides a comprehensive overview of the organization's research activities through the analysis of a limited number of research and development projects, focusing on both past and current research endeavors. The analysis emphasizes the technologies and competencies utilized and the technological outcomes, such as prototypes, which are crucial for evaluating technological maturity based on predefined assessment dimensions. (Hecklau et al. 2023; Hecklau et al. 2022b, 2022a) To assess the technological maturity, an appropriate benchmark is selected for comparison (Werner und Sourder 1997). The auditor's expertise and the organization's research activities form the basis for the evaluation. The auditor outlines the international state-of-the-art in the relevant technological areas and employs the organization's research achievements, such as tangible results from internal projects, as a benchmark. (Hecklau et al. 2022b)

For the assessment of the dimensions, a technological maturity model was developed, comprising different levels. This model serves as the foundation for evaluating an RTO within the scope of the technology audit. The spectrum includes various gradations. Each level is described individually and specifically for each of the assessment dimensions to ensure a high degree of standardization and comparability between different RTOs. To this end, a technological maturity model has been created, consisting of five levels. It starts with maturity level 1, representing insufficient technological maturity, and culminates at maturity level 5, representing very high technological maturity. The technological maturity model is visualized in the following figure 1. (Hecklau et al. 2022b; Hecklau et al. 2023)

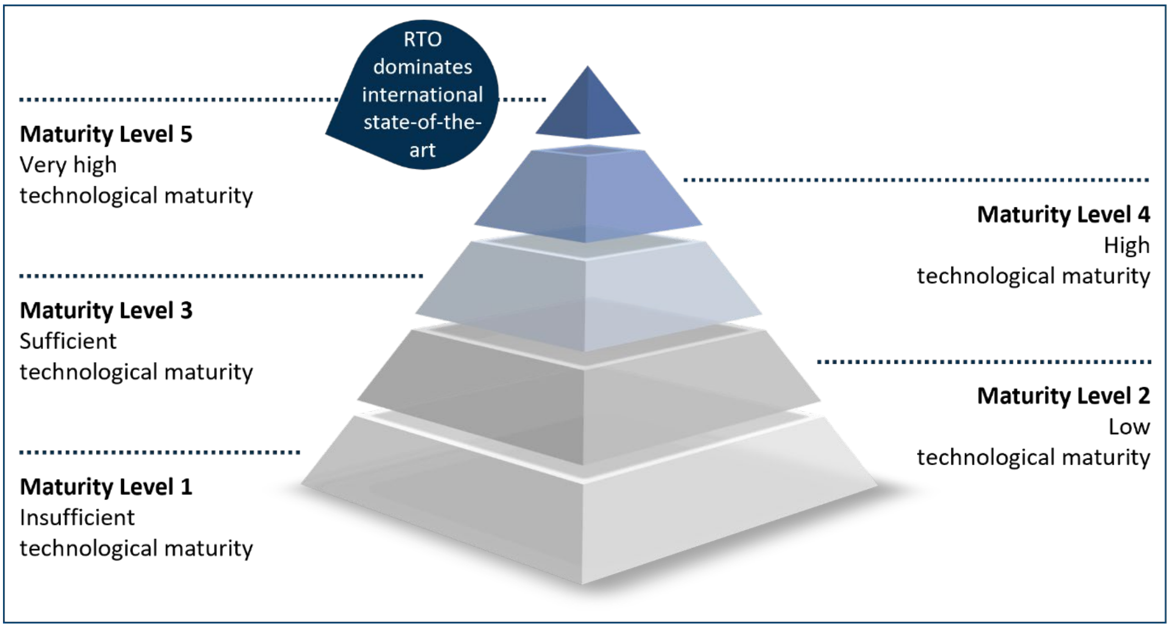

Figure 1: Technological Maturity Model for RTOs

3. Results of 41 Technology Audits at Brazilian SENAI Innovation Institutes

Since 2012, the Brazilian national training service SENAI has been setting up 26 innovation institutes. Under the umbrella organization of Brazilian industry CNI, SENAI is pursuing a network strategy in the development of these applied research institutes, which envisages the establishment of nationally operating institutes with different focus areas in different regions. Figure 1 below provides an overview of all operational SENAI innovation institutes and their respective research focuses.

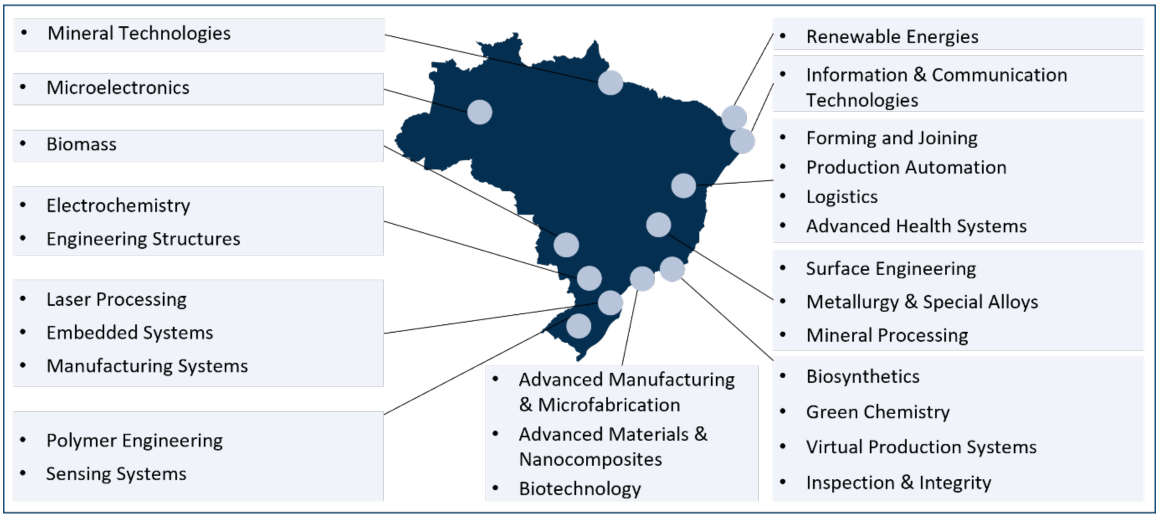

Figure 2: Overview of 26 SENAI Innovation Institutes in Brazil

The institutes offer research and development for Brazilian industry and have a broad thematic and technological focus. They are already an integral part of the Brazilian innovation system. The network is growing steadily and can be seen as a successful example of a large-scale initiative to establish an innovation structure.

All of the 26 operational ISIs were initially technologically audited for the first time between 2017 and 2022. Two rounds of technology audits were conducted between 2017 and 2023. (Hecklau et al. 2019) Due to the Covid-19 pandemic, no audits were performed in 2020, and all audits in 2021 were conducted entirely digitally. In the first round, which concluded at the end of 2019, all 23 operational ISIs at that time underwent technological audits. Of these, 15 ISIs underwent the technology audit again in the second round, which concluded at the end of 2023. Additionally, three new ISIs were audited for the first time in 2022. Figure 3 below provides an overview of the timeline of all technology audits conducted on the Brazilian Innovation Institutes since 2017.

2017	2018	2019	2021	2022	2023
Biomass	Electro Chemistry	Microelectronics	Biomass	Metallurgy & Special Alloys	Mineral Technologies
Sensing Systems	Green Chemistry	Materials & Nanocomposites	Polymer Engineering	Biosynthetics	Engineering Structures
Embedded Systems	Polymer Engineering	Advanced Manufacturing	Sensing Systems	Biotechnology	ICT
	ICT	Virtual Production Systems	Electro Chemistry	Advanced Health Systems	Surface Engineering
	Mineral Technologies	Production Automation	Green Chemistry	Inspection & Integrity	Microelectronics
	Biosynthetics	Logistics	Manufacturing Systems		
	Manufacturing Systems	Forming & Joining	Laser Processing		
	Laser Processing	Renewable Energies	Embedded Systems		
	Metallurgy & Special Alloys	Mineral Processing			
	Surface Engineering	Engineering Structures			

Figure 3: Timeline of 41 Technology Audits at the Brazilian SENAI Innovation Institutes

Valuable insights were gained during the application of the method in this first run. In addition to the method's potential for improvement, results on technological maturity were identified that illustrate the strengths of the methodology and are briefly described below.

3.1 Overall Results

During the first audit round, the assessments of the technological maturity levels by dimension were on average below the threshold value of 3. The technology base was assessed with an average of 2.85, the dimension of products and services with 2.75 and the collaborations with 2.5. A rating of 3 indicates that an institute has sufficient technological maturity to carry out all the research activities it aims for and offers. It has been shown that many ISIs are not able to offer all the intended services and products in all the planned research areas. As a result, the defined research portfolio of the network of ISIs could not be offered to Brazilian industry in its entirety. The audit also revealed that the technology base and products & services were better developed overall than the technological maturity in the area of cooperation. This can be explained by the fact that, particularly in the first years of the network's development, high investments were made to build up the necessary infrastructure and technical resources. The technology base was therefore the best developed compared to the other two dimensions, as the results of the audits show. It is also evident that the ISIs were not yet able to fully translate the inputs available to them into innovative research results at this early stage.

From 2021, the ISIs audited for the first time were subjected to a further technological audit in order to better understand developments at the institutes. To this end, a total of 15 selected ISIs were audited again by 2023. In order to ensure the highest possible degree of comparability, an attempt was made to use the same auditors as in the first round almost across the board. This reapplication of the method has also enabled continuous improvement of the method. One of the most important revisions to the method took place in 2022 in the form of the further specification of the assessment aspects and the introduction of a weighting and an assessment of the dimensions with decimal digits in order to enable even more precise gradations in the assessment.

The evaluation and comparison of the results of the 15 double-audited ISIs revealed significant improvements in all three dimensions. For the first time, these re-audited institutes were able to achieve an average rating of at least 3 in all dimensions, which proves that the network of ISIs as a whole has sufficient technological maturity to carry out research activities. The best rated dimension continues to be the technology base (3.6). The improvement compared to the first round is +0.7 points. The increase in the technology base can be explained by further major investments in the equipment and infrastructure of many ISIs. The products & services dimension (3.2) also improved (+0.5 points), which indicates the improved outputs of the ISIs. Despite these optimizations in the output dimension, it is clear that the now solid technology base (3.6) does not yet result in innovative solutions to a comparable extent (3.2). The lowest rated dimension is still cooperation (3.0), which nevertheless also shows a high improvement rate of +0.6 points. Due to the Covid-19 pandemic in particular, the ISI network cooperated more closely in order to build up joint capacities and knowledge, e.g. for corona tests. Figure 4 below shows the results of both rounds of technology audits for the 15 ISIs audited twice.

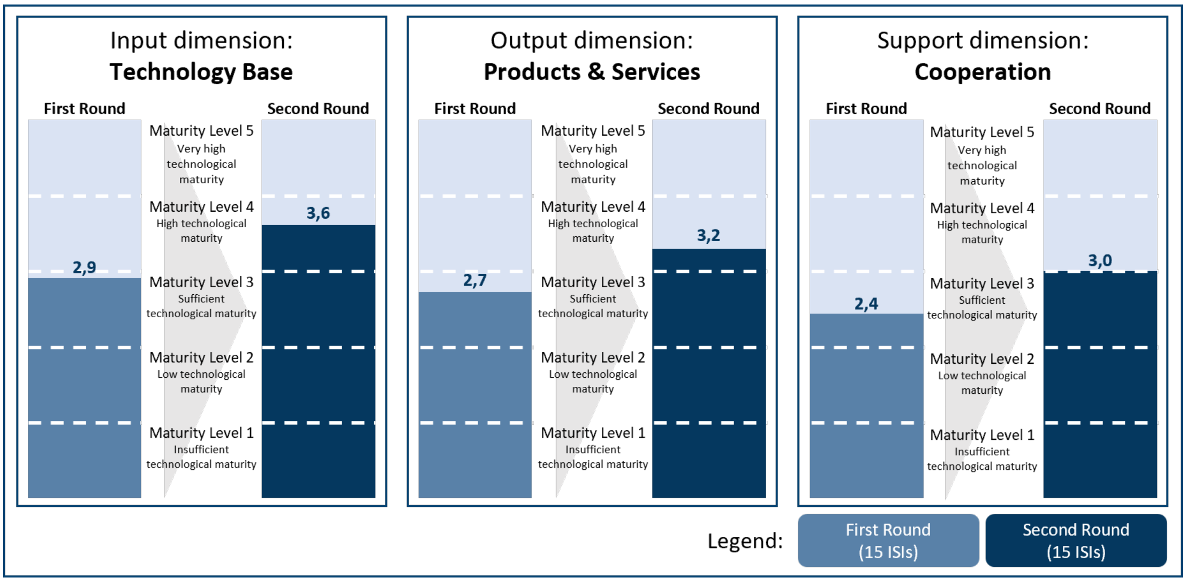

Figure 4: Comparison of Results of Technology Audits

The results of the three dimensions of Technology Base, Products & Services and Cooperation are explained in more detail below.

3.2 Results in Dimension "Technology Base"

The good overall assessment of the technology base can be explained by the high investments made by the Brazilian development bank (BNDES). The reasons for the significant average improvement in the technology base from the first (2.9) to the second round (3.6) at the 15 ISIs where both audit rounds were carried out are that further basic and specific technologies were introduced in the years between the audits. In addition, the skills of employees were stabilized and further improved, e.g. through training or by hiring new employees. Finally, the evaluation of the audits has also shown that the ISIs are aware of future technological developments and that they have a strategy in place to further develop skills, equipment and infrastructure accordingly.

Basic strategies and measures that have proven to be effective in optimizing the technology base in the course of the two audits are

- the installation and commissioning of all technologies already acquired and the search for potential innovative products and services based on unused equipment;
- the strategic purchase of specific equipment if required;
- focusing on the maintenance of existing technologies, laboratories and infrastructure;
- developing effective retention strategies to ensure that the required skills and experience remain within the ISI network;
- further developing the technological skills of ISI staff;
- and the recruitment of a highly skilled, innovative workforce capable of developing cutting-edge technological solutions.

3.3 Results in Dimension "Products & Services"

With regard to the products & services dimension, the results show that the ISIs are able to develop innovative research results to a certain extent. The ISIs were able to improve in the output dimension from the first (2.7) to the second audit round (3.2) and, as of 2021, had a sufficient level of technological maturity on average to transfer state-of-the-art technologies into new and customized products and services. However, there is still room for improvement in the degree of innovation of the products developed. Furthermore, although the ISIs are able to anticipate potential new technological solutions, the successful implementation and realization of the technological roadmaps are not consistently pursued.

Here, too, basic target-oriented strategies and general measures for improving the products & services dimension were identified:

- focusing on the acquisition of large and complex research projects in order to create the opportunity to develop innovative technological solutions by providing sufficient funding and time;

- improving the level of innovation of technological products and services, e.g. by
- *integrating knowledge, ideas and solutions from partners such as ISIs, universities and industry partners;*
- *increasing efforts to carry out pre-competitive applied research activities (from market pull to technology push);*
- the follow-up of technological roadmaps to ensure successful implementation and realization.

3.4 Results in Dimension "Cooperation"

Cooperation was assessed as sufficient at network level. Its maturity level has improved on average from the first (2.4) to the second audit round (3.0). Internal cooperation between the ISIs is at an expandable level, but is sufficient to jointly develop ideas for new technological products and services. In particular, cooperation to combat the covid-19 pandemic has significantly improved this dimension.

Cooperation with external R&D partners and service and technology providers for the integration and use of external technologies takes place to a limited extent. At an international level, there are only a few partners for the joint implementation of research activities and the development of innovative technical solutions.

Strategies and general measures to optimize cooperation that have proven effective in the double audit are

- the search for valuable win-win partnerships with other ISIs, universities, industrial partners, etc. in order to incorporate their knowledge, competencies, ideas, technologies, etc. and thus
- *increase the degree of innovation of its own technological solutions;*
- *close own technological gaps;*
- *close gaps in the skills and experience of its own employees;*
- *jointly develop innovative technological ideas;*
- take advantage of local cooperation between ISIs in the same city/campus and build on their own local strategies without neglecting the overarching guidelines and goals of the entire ISI network;
- to strengthen international cooperation for the joint implementation of research activities in order to become more visible within the international innovation system.

4. Conclusion and Implications Improvement of the Technology Audit

The application of the technology audit method to assess the technological maturity of Research and Technology Organizations in Brazil has shown important implications. Over a period of seven years, the method was applied intensively and comprehensively in 41 audits, providing valuable insights and experience on its effectiveness.

Based on the results of the 15 ISIs audited twice, it can be concluded that technological maturity has fundamentally improved in all dimensions. In addition to the general further development of the ISIs, the strong result is also attributable to the recommendations of the technology auditors from the first round. The recommended measures were largely taken into account and implemented, thus supporting the systematic development of the ISIs' technological maturity.

This broad application of the technology audit methodology has demonstrated that the technology audit is an effective tool for assessing the technological maturity of Research and Technology Organizations. Based on the findings, several directions for further development of this method can be identified to enhance its applicability and validity.

A central aspect for future development lies in further detailing the existing maturity model. This could involve incorporating significant Key Performance Indicators (KPIs) that measure specific aspects of technological and organizational maturity, thus providing a more nuanced picture of an RTO's technological maturity. The technology audit was specifically developed and tested for Research and Technology Organizations. A potential extension could involve adapting and validating the method for other organizations (e.g., universities) engaged in research and development. This would not only increase the scope and relevance of the method but also test its robustness and flexibility in different institutional contexts. Another important development perspective involves adding further evaluation elements and aspects. The dynamics of the national innovation system, in which RTOs operate, are subject to continuous changes. These changes could impose new requirements on the evaluation criteria. Therefore, it is essential that the evaluation elements and aspects consider specific developments in the innovation system to ensure the relevance and timeliness of the assessments.

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