Evaluating Sustainable Implementation of National Innovation Systems through Technology Audits: Evidence from Brazil's SENAI Innovation Network

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Abstract: As evidence of the successful implementation of SENAI's national network of 28 Innovation Institutes in Brazil, this paper summarizes longitudinal results from two rounds of technology audits conducted between 2017 and 2025. The audits are part of an overall strategic planning approach that includes business model development, implementation support, and recurring evaluation in order to support the systematic establishment of a macro-level innovation system in an emerging economy. Within this context, a standardized technology audit methodology was applied across three core dimensions: technology base, products and services, and cooperation. Twenty-three institutes completed two audit cycles and therefore constitute the longitudinal sample, enabling an analysis of development at institute and network level. The results show consistent and relevant improvements of 24% in the technological base, including equipment, infrastructure, and competences. Improvements of 20% can be observed in the technological products and services developed by the institutes, while cooperation activities within the innovation system, for example with industrial and research partners, increased by 23% from the first to the second audit cycle. The paper presents results and key learnings from eight years of technological evaluation and discusses how such approaches can support the sustainable implementation and strategic development of innovation systems and structures.

Keywords: Sustainable business model implementation, Evaluation, Technology audit, Technology assessment, Innovation management

1. Introduction

Research and technology organizations (RTOs) play an important intermediary role between scientific knowledge creation and industrial application (EURAB 2005; OECD 2011). By transforming research results into industrially relevant technologies, products, and services, they contribute significantly to the innovative capacity and overall performance of national innovation systems (Freeman 1987; EARTO 2016; Hecklau et al. 2020). In emerging economies the establishment of such intermediary organizations is particularly challenging. In contrast to more mature innovation environments, key preconditions for successful operation, including technological capabilities, market-oriented demand, qualified human resources, and stable cooperation structures, often have to be developed simultaneously (Bell and Pavitt 1992; Mazzoleni and Nelson 2007). As a result, the development of RTOs is not merely an organizational task, but a broader systemic process that depends on the coordinated evolution of multiple innovation-related capacities. Brazil provides a particularly relevant case (Figueiredo 2014). Since 2012, the SENAI Innovation Institutes have been established as a national applied R&D network to raise the innovation capacity and competitiveness of Brazilian industry, established by SENAI, and the National Confederation of Industry, supported by the Brazilian Development Bank, and Fraunhofer partners (Kohl et al. 2020).

Research infrastructure alone is not sufficient to ensure the successful development of applied R&D institutes. The central challenge lies in enabling these institutes to evolve into robust, demand-oriented, and technologically advanced organizations. This requires suitable management methodologies and instruments that support a systematic analysis of their technological status quo and development needs. For strategic steering, it is essential to understand whether institutes possess an adequate technology base, whether they are able to translate this base into valuable technological results, and whether they are sufficiently embedded in cooperation structures that broaden and strengthen their capability set. In the SENAI context, this challenge clearly revealed the need for a suitable methodology to analyze and evaluate the technological maturity of the institutes. As a consequence, a technology audit methodology specifically designed for applied R&D organizations was developed and applied over the long term (Hecklau et al. 2022, 2023; Hecklau 2024).

Against this background, this paper analyzes the longitudinal results of two rounds of technology audits conducted between 2017 and 2025 for 23 SENAI Innovation Institutes in Brazil. To provide the necessary analytical context, the paper first briefly introduces the technology audit methodology and its underlying assessment logic. It then presents the results of the two comprehensive audit rounds and compares the findings across both periods, with particular attention to the observed changes in the assessed dimensions. Based on these results, the paper derives key insights for the further development of the SENAI Innovation Institute network and discusses broader implications for the sustainable implementation of national innovation systems and the governance of applied R&D networks. This perspective is particularly relevant because sustainable industrial transformation depends not only on individual technologies, but also on capable institutions that generate, adapt, and diffuse such technologies over time.

2. Methodological Background of the Technology Audit

The technology audit is a methodology designed to analyze and evaluate the technological maturity of applied R&D organizations. Its purpose is to provide a structured understanding of whether an organization possesses the technological resources, capabilities, and external linkages required to perform state-of-the-art research and development and to translate these activities into technologically relevant results for the industry. In this respect, the method extends beyond the assessment of managerial routines or quantitative output indicators by focusing specifically on the technological maturity of an organization.

To assess this maturity, the technology audit examines three core dimensions: Technology Base, Products and Services, and Cooperation. The dimension Technology Base addresses the technological and organizational foundations of R&D activities, including technological strategy, infrastructure, equipment, and competences. Products and Services focuses on the extent to which these foundations are translated into technologically advanced and market-relevant results, such as innovative solutions for industry. The dimension Cooperation assesses the extent to which an organization is embedded in relevant technological partnerships and innovation networks that complement and expand its own capability base (Etzkowitz and Leydesdorff 2000). Taken together, these dimensions allow for a comprehensive assessment of the technological status quo and development needs of an applied R&D organization.

The technology audit was developed through method engineering, which supports the systematic construction of context-specific methods from established method elements (Henderson-Sellers et al. 2014). Its development was based on a structured synthesis of 30 sources. In particular, six existing approaches were analyzed in depth as methodological foundations: the evaluation of industry-oriented research organizations, the Technology Effectiveness Audit Model, the Technology Management Process Assessment, the Technological Capability Assessment, the Model for Technological Capability Assessment in R&D Centers and the Strategic Business Planning Procedure (Kuhlmann and Holland 1995; Garcia-Arreola 1996; Phaal et al. 2001; Rush et al. 2007; Mohammad et al. 2010; Kohl et al. 2020). Broader research on RTO evaluation informed the RTO-specific context of the method (Martinez-Vela 2016). The resulting technology audit was subsequently refined through repeated applications in Brazil (Hecklau et al. 2019; Hecklau 2024). The procedure combines standardization and expert judgment. Standardization is ensured through a common maturity model, predefined dimensions and assessment items, structured templates, and clearly defined workshop steps. Expert judgment is incorporated through the involvement of a technology auditor with domain-specific research experience, thereby enabling a deeper qualitative assessment of the institute's technological profile (Hecklau et al. 2022). This combination is essential, since technological capability cannot be assessed adequately through document analysis alone.

Table 1: Dimensions of the Technology Audit

Dimension	Analytical Role	Assessment Items
Technology Base	Input dimension: analyses the technological and organizational inputs required to carry out the R&D activities of an RTO and assesses the extent to which these inputs are sufficiently mature to support the delivery of the institute's defined R&D services.	Technologies, infrastructure, equipment/software, competences, and technological strategy used to execute R&D projects.
Products and Services	Output dimension: analyses the technological results generated through R&D activities and assesses the extent to which the institute translates its technological base into innovative products and technological services relevant to industry.	Complexity and innovativeness of R&D results and the translation of technologies into industrial solutions, products, and services.

Dimension	Analytical Role	Assessment Items
Cooperation	Support dimension: analyses the cooperation structures that support R&D activities and assesses the extent to which the institute is connected to the right partners in order to complement its own capabilities and generate innovative technological results.	Technological synergies through collaboration with RTOs, universities, companies, service providers, customers, and the wider innovation ecosystem.

The audit process follows a standardized approach (Hecklau et al. 2022, 2023) that is designed to generate a comprehensive and reliable understanding of the technological maturity of an applied R&D organization. It begins with a preparation phase in which the relevant information on the R&D portfolio, competences, equipment base, and service areas is collected and reviewed in order to ensure a sufficiently robust basis for the assessment. The subsequent audit process focuses on the analysis of the institute's R&D strategy, its past and ongoing projects, its laboratory infrastructure and technological resources, its position in relation to relevant benchmarks and the state of the art, as well as its future technological development perspectives. The findings are synthesized in a structured report as basis for further developments. In the SENAI application context, this process was supported by on-site visits in Brazil and, where required, by the remote participation of additional technology experts (Hecklau et al. 2023).

The assessment itself is based on a standardized five-level maturity scale. Maturity level 1 denotes minimal technological maturity, whereas level 5 represents very high technological maturity in relation to the analyzed state of the art and relevant benchmarks. A score of 3 indicates sufficient maturity to perform R&D activities in the respective technological service areas of the institute. Scores of 4 or higher indicate the capability to conduct complex R&D activities and to develop highly innovative technological solutions (Hecklau et al. 2022; Hecklau 2024).

This methodology formed the methodological basis for its long-term application in the SENAI Innovation Institute network in Brazil. The following section presents and discusses the results generated through these technology audits.

3. Results

Since 2017, the technology audit has been applied systematically within the SENAI Innovation Institute network in Brazil (Hecklau et al. 2019, 2024). Of the network's 28 institutes, 23 had been operational long enough to complete two full audit cycles and form the longitudinal sample of 46 technology audits. Three newer operational institutes had completed one audit each, bringing the total to 49. Two further institutes were still under implementation and had not yet been audited. The audits were supported by 18 Fraunhofer Institutes, whose technology experts contributed as auditors across the different technological fields.

The results of these 46 technology audits provide a robust basis for assessing technological development over time at both institute and network level. The following analysis first presents the aggregated results across the three core dimensions before discussing selected patterns and implications in detail.

The most important finding is the consistent improvement across all three dimensions between the first and second rounds of technology audits. According to the consolidated results, the average maturity score in Technology Base increased from 2.9 to 3.6, corresponding to an improvement of 24%. In Products and Services, the average score rose from 2.7 to 3.2, representing an improvement of 20%. Cooperation increased from 2.5 to 3.1, corresponding to an improvement of 23%. This development is particularly relevant as the first-round averages were still positioned around the threshold between low (<3) and sufficient maturity (=3), whereas the second-round averages are clearly located within the range of sufficient maturity (>3) and, in the case of Technology Base, already move towards a more advanced maturity level. Figure 1 illustrates these developments.

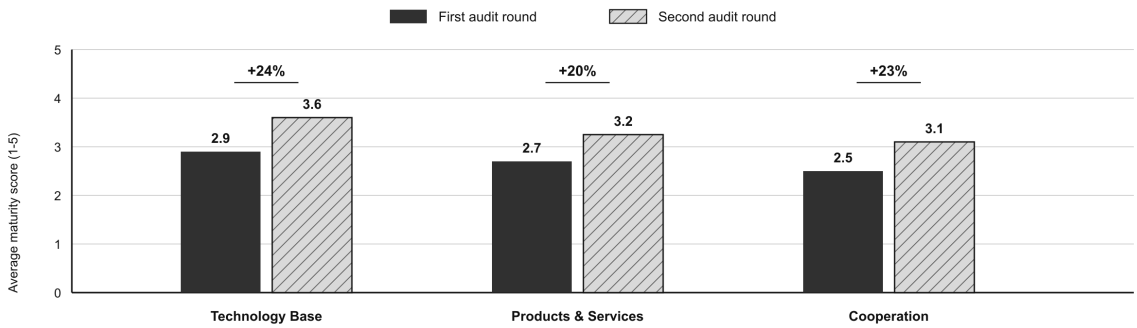


Figure 1: Average maturity levels across the two audit rounds based on the consolidated results

Beyond the aggregated results presented above, a more differentiated view of the three assessment dimensions provides further insights into the technological development of the network over time.

The highest average scores were achieved in the dimension Technology Base. This pattern is plausible in light of the developmental logic of a newly established applied R&D network. Substantial early investments, particularly those financed by the Brazilian Development Bank BNDES, in laboratories, equipment, software, and staff qualification created the necessary preconditions for later innovation activities and contributed significantly to the comparatively strong results in this dimension. The observed increase therefore reflects more than incremental progress. Rather, it indicates that many institutes advanced from a stage characterized by partial capabilities and limited technological resources towards a more systematic, credible, and operationally robust basis for conducting R&D activities.

The development in Products and Services is equally noteworthy, as this dimension captures the extent to which technological resources are effectively translated into relevant R&D outputs. With an average score of 3.2 in the second audit round, the network moved beyond a stage primarily characterized by isolated activities or lower-complexity project work and reached, on average, a level of sufficient technological output maturity. This suggests that the institutes increasingly succeeded in converting their installed competences and technological resources into innovative and industrially relevant offerings.

Cooperation also improved substantially over time. This result is plausible, as cooperation depends not only on the internal maturity of an institute, but also on external conditions such as the availability of suitable partners, complementary competences, and the broader density and quality of the surrounding innovation ecosystem. The observed increase therefore suggests that cooperation is the dimension in which institutional development and external framework conditions interact most strongly. While technological capability can be strengthened within an institute through targeted investments and capability-building measures, cooperation additionally requires relational embeddedness and institutional alignment beyond the boundaries of the individual organization.

A further important finding concerns the qualitative significance of maturity level 3. In the first audit round, the average values across all three dimensions were still located close to the threshold under sufficient maturity. In the second round, all aggregate values exceeded this threshold. This indicates that the network, on average, reached a level at which the institutes were no longer merely operational, but sufficiently mature to perform their research activities in a structured and strategically guided manner. Given that maturity level 4 denotes the ability to address complex R&D tasks and generate highly innovative solutions, the central challenge is no longer basic stabilization, but the selective advancement of institutes and dimensions towards more advanced levels of technological performance.

4. Discussion

The results support a staged interpretation of institutional capability building in applied research networks. Technology Base appears to function as the enabling foundation for the further development of applied R&D institutes. Investments in scientific equipment, laboratory infrastructure, software, technological strategy, and staff competences produced the clearest and earliest gains. In the SENAI case, this development was supported in particular by targeted investments, including funding provided through BNDES. Despite comparatively high staff turnover in parts of the network, technological competences were increasingly stabilized through training measures and strategic recruitment. At the same time, future technological trends were increasingly identified and reflected in strategic considerations regarding the further development of infrastructure and skills. These

developments help explain why Technology Base achieved the strongest average results across the three dimensions.

Products and Services also improved considerably, indicating that capability building did not remain confined to internal resource accumulation, but increasingly translated into relevant technological outputs. This is particularly important, as the dimension captures whether the installed competences and resources of an institute are effectively converted into customized technological solutions, products, and services for industry. The results suggest clear progress in this regard. At the same time, they also indicate that the generation of highly innovative outcomes remains a developmental task rather than a fully achieved state across the network. While technological roadmaps and strategic orientations for future service development are increasingly in place, their consistent implementation appears to remain an important field for further strengthening the output side of the institutes.

Cooperation improved as well. This result is plausible, as cooperation depends not only on the internal maturity of an institute, but also on the availability of suitable partners, complementary competences, and the broader quality of the surrounding innovation ecosystem. The findings suggest that collaboration has improved particularly at the local and regional level. However, internal collaboration across the SENAI Innovation Institutes still appears not sufficient to systematically enable joint technological development within the network. In addition, cooperation with international and other external R&D actors remains comparatively limited, leaving untapped potential for the co-creation of more advanced and innovative technological solutions. In this sense, cooperation remains the dimension in which institutional maturity and systemic context interact most strongly.

From a governance perspective, the findings underline the value of technology audits as more than an isolated evaluation instrument. In the SENAI context, they form part of a broader strategic management architecture that links planning, implementation, and evaluation (Kohl et al. 2020). Alongside the technology audits, management audits / management pacts are conducted that focus more strongly on the implementation of institute strategies and also incorporate more conventional innovation and performance indicators, such as revenue, patents, or project counts (Kohl et al. 2020; Hauschildt et al. 2023). The specific contribution of the technology audit lies in complementing this perspective by making technological maturity visible in a structured and comparable way. It extends the evaluation logic beyond managerial implementation and conventional innovation KPIs by linking resource endowment, technological output, and cooperation capacity within a common maturity framework. In this way, it helps to explain not only whether institutes perform, but also how far they possess the technological capability base required for sustainable performance.

The maturity scores used in this study are based on expert assessments. Although they follow a standardized approach, they are not directly comparable to conventional performance indicators such as revenues, patents, or scientific output. Moreover, the technology audit concept was refined over time through the introduction of additional methodological detail, including an updated version from 2023 onward. At the same time, the core dimensions and the underlying maturity logic remained stable, thus ensuring the comparability of the results (Hecklau et al. 2023). Furthermore, the longitudinal comparison presented here is limited to the subset of institutes for which two complete audit rounds were available in the consolidated final material. Future research should therefore aim to link audit results more systematically with performance and impact indicators at project, institute, and regional level. The present paper reports consolidated mean scores and does not include institute-level dispersion measures or paired significance tests. The observed changes are therefore interpreted descriptively rather than as statistically significant effects. Future analyses should apply paired tests to the underlying institute-level scores and report appropriate dispersion measures.

5. Conclusion

This paper analyzed the longitudinal development of 23 SENAI Innovation Institutes in Brazil based on two rounds of technology audits conducted between 2017 and 2025. The results show consistent improvements across all three dimensions of technological maturity and indicate that the network has moved from an initial ramp-up phase towards a more stable and technologically credible level of operation.

The broader innovation system relevance of these findings becomes clearer when they are related to external evidence. Brazil ranked 52nd in the Global Innovation Index 2025 and is identified as an economy that continues to overperform relative to its level of development (WIPO 2025). At the same time, a recent macroeconomic impact study by Fraunhofer IPK and Fraunhofer ISI found that the SENAI Innovation Institutes induced 0.66% of Brazil's GDP, with positive and statistically significant effects on regional GDP per capita (Kohl et al. 2025; Schubert et al. 2025). The present paper operates at a different analytical level, yet the findings are

complementary. The macro study shows that the network matters economically. The technology-audit results help explain why: over time, the institutes built stronger technological foundations, produced more advanced outputs, and intensified relevant cooperation. In this sense, repeated technology audits can be interpreted as a micro-to-meso governance mechanism that supports macro-level impact.

Overall, the paper underlines that the sustainable implementation of applied R&D networks depends on the systematic development of technological capabilities, output-oriented competences, and cooperation structures over time. In this regard, the technology audit provides a useful methodology for strategic steering and long-term governance.

Ethics Declaration: This research did not involve human participants, personal data, medical data or experimental procedures requiring ethical approval. The paper is based on applied research carried out by the authors, literature analysis, previously published research and publicly available or institutionally approved case evidence. Therefore, no formal ethical clearance was required.

AI Declaration: AI-based tools were used to support proofreading and English language refinement, including spelling, grammar and wording corrections. This was done because the authors are not native English speakers. The authors reviewed the final manuscript and take full responsibility for its accuracy, originality and integrity.

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