

Technology Audit: Procedure for the Assessment of the Technological Maturity of Applied R&D Organizations

Fabian Hecklau¹, Florian Kidschun¹ and Holger Kohl²

¹ Fraunhofer IPK, Division Corporate Management, Berlin, Germany

² Technical University of Berlin, Department Sustainable Corporate Development, Berlin, Germany

fabian.hecklau@ipk.fraunhofer.de

florian.kidschun@ipk.fraunhofer.de

holger.kohl@tu-berlin.de

Abstract: Applied research and development (R&D) organizations – or research and technology organizations (RTOs) in a broader sense – strive to develop technological solutions that translate results from research and science into state-of-the-art products and services. This can only be achieved if technological resources and competences are effectively and efficiently used to build up competitive advantages. Therefore, the assessment of the technological capability can provide applied R&D organizations with information on strengths and weaknesses in their specific technology areas, on the basis of which technology strategies can be derived to contribute to the development and training of substantial (core) competences, which in turn improve the quality of unique and differentiating products and services. The main objective of this paper is to describe the technology audit as a procedure for evaluating the technological maturity of applied research organizations. Hence, the focus will be put on the technological capabilities needed to execute the intended research activities on the way to becoming a reference in the respective technology area. In addition, the aim of the application of the procedure is to provide a detailed insight into the working methods of research institutions with focus on the R&D portfolio (e.g. complexity of R&D projects). Furthermore, the sustainable impact of R&D projects of the applied R&D organization (e.g. optimizations of customers processes) will be discussed, as well as the used & developed technologies and the necessary competences to generate innovative solutions for the Brazilian industry.

Keywords: Technology, Technological Capability, Technological Resources, Technological Competences, Technology Evaluation, Strategic Technology Management, Research and Technology Organizations, RTO, Applied R&D

1. Introduction

The *technology audit* presents a suitable methodology and approach for the assessment of the technological maturity of an applied R&D organizations and in a broader sense also of RTOs within a workshop procedure (Rubenstein and Geisler 1991; Porter 1978). In the following, it will only be referred to the term *RTO* which will here denote RTOs in a broader sense as well as applied R&D organizations. The technology audit mainly focusses on the analysis of projects within the R&D service areas of the RTO in order to get a comprehensive understanding of the used technologies, research competences, developed technologies as well as the established technological partnerships of the RTO.

The methodology of the technology audit has been developed over a long period of time and has been updated constantly. This paper provides a brief summary of the methodology itself and is the condensed outcome of previous research work. The derivation of the methodology as well as the previous academic work that lead to this paper can be found in the following publications: (Hecklau et al. 2019a; Hecklau et al. 2019b; Hecklau et al. 2019c; Hecklau et al. 2020a, 2020b, 2020c).

2. Method of technology audit

The technological performance of RTOs is analyzed and subsequently assessed with the help of the technology audit assessment procedure. For this purpose, a standardized procedure is available in addition to various models, such as the maturity model or the assessment dimensions model, as well as the tools and templates (see chapter 3). This procedure enables a structured assessment of the RTO to be audited. The three main steps and a fourth optional step are described in Figure 1 below.

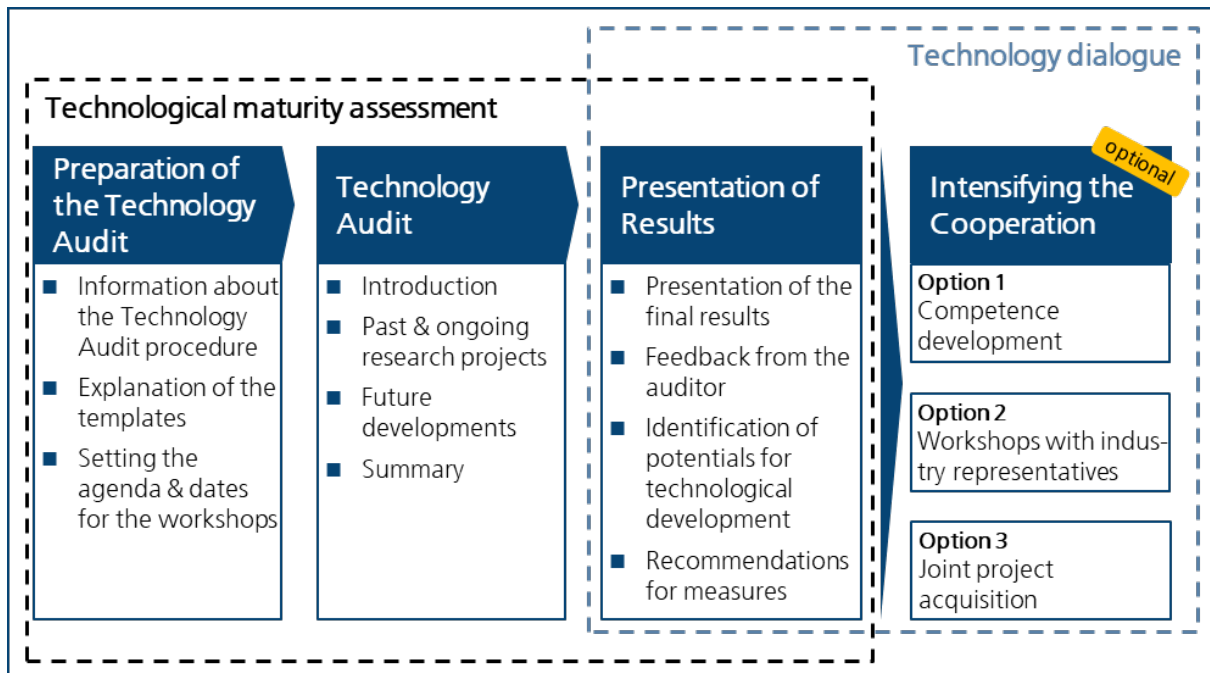


Figure 1: Technology audit procedure

The procedure consists of two main parts. In the mandatory part of the *technological maturity assessment*, the technology audit takes place. For this purpose, there is a *preparatory session*, the *technology audit workshop*, and the *final presentation and discussion of the auditor's assessment results*. The second and optional part is called the *technology dialog*. The aim of this part is a further cooperation between the technology auditor and the organization to be audited. For this purpose, for example mutual competence development is aimed based on the results of the assessment of technological maturity. Activities to initiate joint research activities, such as workshops with industry representatives or joint project acquisitions, are also possible. It is important that the neutrality of the auditor is ensured despite of any intended further cooperation.

The individual steps of the technology audit procedure are described in detail below.

2.1 Preparation of the technology audit

Before the technology audit process begins, it needs to be determined who will take on the role of technology auditor and perform the assessment of the technological maturity of the RTO to be audited. To this end, a technology expert who is active in a similar thematic focus as the RTO is assigned. It is important to ensure that the technology auditor is also active in the field of applied research and is familiar with the relevant specifics of RTOs. Furthermore, the auditor must have broad expertise and experiences. In addition to the auditor's neutrality, he should have excellent communication skills.

In the first workshop, the *preparation of the technology audit*, the auditor receives information from the RTO in order to obtain an overview of the R&D portfolio, research competencies, products & services, and other technical information. Moreover, information on the main activities, technological equipment, and employee competencies is provided so that the auditor can gain a comprehensive initial overview. In a preparatory workshop, which can be conducted on-site or online via video call, the RTO and the technology auditor have the opportunity to talk directly for the first time. On the one hand, the procedure and the underlying method of the technology audit are presented in detail, and on the other hand, the provided documents are discussed. There is the possibility to clarify the first open technical questions. Furthermore, the auditor can request missing or further information from the RTO, which is necessary for the preparation of the technology audit workshop. This step serves to guarantee the quality of the later assessment, as it can be ensured that all necessary information is available.

2.2 Technology audit workshop

In the step of the *technology audit workshop*, the technology auditor analyses the various service areas of the RTO on-site and determines the technological maturity.

In this two-day workshop, a total of four sessions are conducted, each focusing on a different thematic block: Session 1: Introduction to the technology audit; Session 2: Analysis and evaluation of past and ongoing research projects; Session 3: Future developments; and Session 4: Summary.

In order to allow for an in-depth and open discussion, there are no strict definitions or time limitations for each session. Instead, a generous block of time will be set for each session, during which the content can be worked on flexibly. The following Figure 2 summarizes the agenda for the two days of the *technology audit workshop*.

Day 1		Day 2	
Session 1: Morning	Introduction • Presentation of the method / procedure of the technology audit • General presentation of the organization to be audited • General presentation of the auditor's organization • Guided tour of the organization to be audited and of the laboratories	Session 3: Morning	Future Developments • Technical discussion of planned research topics and research projects in acquisition • Analysis of potential technological developments in all service areas of the organization to be audited
	Past & Ongoing Research Projects • Analysis of all service areas of the organization to be audited • Technical discussion of representative completed and ongoing research projects • Presentation of comparative projects by the technology auditor		Summary • Initial preliminary assessment of the technological maturity of the organization to be audited in terms of: • Technology Base • Products & Services • Cooperation

Figure 2: Agenda for the technology audit workshop

The four sessions mentioned above provide the framework for the technology audit workshop and are described in detail below.

2.2.1 Session 1: Introduction to technology assessment

In the first session of the technology audit workshop, basic information is discussed. First, the technology audit procedure and the underlying analysis and assessment methodology are presented. It is important that the technology auditor and the organization to be audited develop a common understanding of the goals of the workshop as well as the approach. The organizations then introduce themselves to each other. In a general presentation of the RTO, basic information such as organizational size, service areas or organizational structure is presented. The auditor also introduces the own organization and provides insight into the own research areas. To create an understanding of the technology base of the RTO, a tour of the organization and the laboratories is conducted. As RTOs basically work on R&D projects with a focus on technological developments. The technology auditor has the opportunity to analyse the technology in detail and to understand how they are embedded in the infrastructure. In addition, there is the possibility to interview employees of the RTO on the respective machines they operate and thus gain insight into the technological competencies.

2.2.2 Session 2: Analysis and evaluation of past and ongoing research projects

In this session, all service areas of the RTO are analyzed. A pragmatic and goal-oriented approach is the selection and discussion of specific and representative research projects that have been carried out in the respective service areas. In this way, a very comprehensive overview of the research activities of the entire organization can be obtained via the analysis of a limited number of research projects. The focus in this session will be on past and current research projects. The technologies and competencies used on the one hand and the technological results in the form of, for example, prototypes on the other are particularly important in the analysis of the research projects. This focus enables the subsequent evaluation of technological maturity

according to the defined evaluation dimensions (see chapter 3). In order to be able to evaluate the technological capability and thus technological maturity, a suitable benchmark must be selected for comparison (Werner and Sourder 1997) with regard to which the maturity level is subsequently evaluated. The expertise and research activities of the technology auditor are the basis for this purpose. The auditor uses the research achievements of the own organization (e.g. concrete technological results from own research projects) as a benchmark and presents these during the session. The final technological assessment of the RTO refers to the auditor's own reference projects that were presented. During this session, the technology expert gets a deep insight into the individual service areas of the RTO as well as the technological equipment and the competencies of the team.

2.2.3 Session 3: Future developments

In this session, future technological developments of the RTO are discussed. The focus is set on the analysis of planned research topics that can be realized through possible research projects that are currently being acquired. On the one hand, it will be discussed how the technology base can be secured. The central question is which further technologies need to be acquired to ensure that a high level of research services can continue to be offered in all service areas in the future. On the other hand, it is discussed which technological innovations will be targeted as a result of research activities of the RTO in the future. In order to be able to understand future envisaged technological developments, technology roadmaps and other tools are used, which the RTO uses for planning and forecasting.

2.2.4 Session 4: Summary

This session offers the possibility to summarize the findings of the previous discussions. The technology auditor has the last chance to address and clarify any open questions. Once the auditor has gained a comprehensive insight into the activities of all service areas, representative research projects, technologies used, own technological developments, competencies and collaborations, an initial and preliminary assessment of the technological maturity can be made. In doing so, the technology auditor evaluates the three defined assessment dimensions: Technology base, products & services, and cooperation. This initial assessment is further refined in the subsequent steps and can be adjusted again by the technology auditor for the final assessment.

2.3 Presentation of results

After the technology audit workshop, the technology auditor prepares a report containing the results of the analysis and the assessment of the RTO's technological capability within the following two weeks. For this purpose, the technological maturity of the RTO is evaluated and compared with reference projects and research achievements of the technology auditor, that have been discussed and presented during the technology audit workshop. The report also includes further detailed analyses of the technology base, products & services, as well as synergistic collaboration with partners at the technological level.

In the next step, the presentation of results, the final assessment and the results of the technological maturity of the RTO are presented in an online meeting via video call or alternatively on-site at the audited RTO. These results are discussed in detail and the auditor gives advice for a concrete action plan to improve the technological maturity. In addition, the RTO has the opportunity to comment on the assessment. The goal of the *presentation of results* is to obtain a common understanding about the final assessment and to identify concrete improvement potentials. The step *presentation of results* forms the interface between the formal assessment of technological maturity and the optional continuation of the cooperation between the technology auditor and the audited organization.

2.4 Intensifying the cooperation

After the technology auditor and the RTO have discussed in detail their respective research activities and learned about their technological strengths and weaknesses, there is the possibility of further collaboration. To this end, the knowledge gained, and the relationship built up to this point can be used to work towards common goals. There are several options for how to deepen the collaboration. For example, efforts can be made to further improve technological competencies on both sides. Competence development workshops can be held for this purpose. In addition, joint research ideas can be further developed, leading to joint research proposals, which would enable funding for the substantive cooperation. It is also conceivable that potential customers can be acquired jointly and that the bundled competencies of the technology auditor and the RTO can be particularly appealing to the potential customer.

3. Elements of the assessment procedure

The methodology of the technology audit for the technological assessment of RTOs consists of several elements. Besides conceptual elements that provide the framework for the methodology, further tools and templates are available as key elements of the technology audit. The most important ones are described in the following chapter.

3.1 Conceptual elements

Conceptual elements, which are described in this chapter, are basic concepts that are used within the technology audit procedure. Besides the assessment dimensions, which are analyzed and assessed in detail during the technology audit workshop, the maturity model is another crucial conceptual element. The maturity model allows a standardized assessment based on five maturity levels.

3.1.1 Assessment dimensions & assessment elements

Three main dimensions form the basis for the assessment. These dimensions target the RTO's technology base, products and services, and collaborations. Within the assessment dimensions, further assessment items are defined. These concretize the dimension and enable a targeted assessment within the technology audit. The three main dimensions are shown in the figure below.

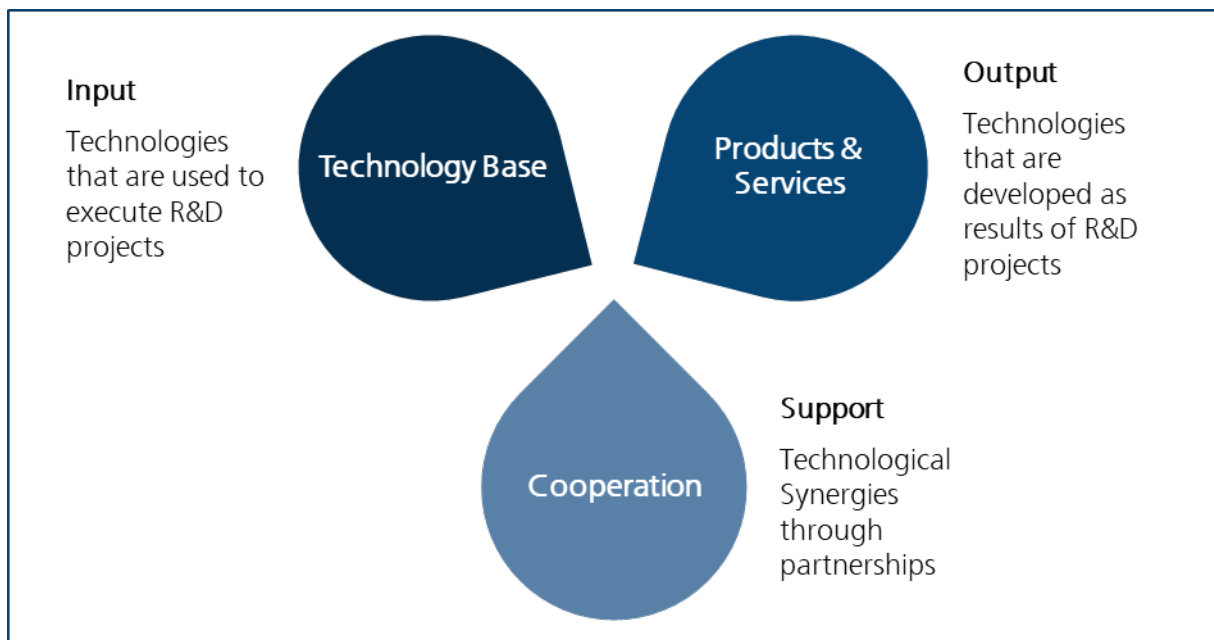


Figure 3: Dimensions of the technology audit

On the one hand, the *technological base* of the RTO will be analyzed and assessed. This dimension serves as the "input-dimension" as technologies as well as competences, that are available and actually used for the execution of R&D projects, are evaluated. The output-dimension, which is called *products & services*, focusses on the results of the executed R&D projects. In this dimension, technologies that are developed as products or technological services are analyzed and assessed. In the third dimension, the *cooperation*, technological synergies through partnerships are evaluated. In this context, partners that support the execution of R&D projects are put into focus.

In the following chapter, the three dimensions will be further explained and operationalized.

- Technology Base

As the dimension *technology base* focusses on the technologies and competences of the RTO that are available and used to execute R&D projects, the leading question for assessing this dimension can be formulated as follows: *Is the RTO capable of executing R&D projects in its defined technology & service areas on a state-of-the-art level?* To answer this leading question, three main items can be identified and operationalized with other key questions.:

- Core competences: Does the RTO possess the necessary core competences to cover its defined research areas and to deliver its defined products & services?
- Technologies, equipment and infrastructure: Does the RTO possess the necessary technologies, core equipment and infrastructure to cover its defined research areas and to deliver its defined products & services?
- Future technology developments: Is the RTO aware of future technology developments and does it have a strategy to evolve competences and infrastructure accordingly?

- Products & Services

As the dimension *products & services* is mainly focusing on the results of research, development and innovation projects and on the creation of innovative solutions, the leading question is the following: *Is the RTO actually executing R&D projects in the defined R&D / service areas and transforming technologies into innovative applications / products with a high impact and clear benefits for the industry?* The following items and operational key questions are analyzed and assessed:

- Execution of R&D projects: Is the RTO de facto executing and delivering R&D projects with an ambitious degree of complexity in all of its defined research / service areas?
- Transformation of state-of-the-art technologies into products and services: Is the RTO transforming state-of-the-art technologies into innovative applications, products and services with a high impact and benefit for the industry?
- Potential new technological solutions, products and services: Is the RTO aware of potential new technological solutions, products and services to increase its competitiveness and pursue a unique selling proposition on the market?

- Cooperation

On the *cooperation* dimension, the level of integration of the RTO within the regional, national, or even international innovation ecosystem is analyzed and assessed, in order to get access to complementary research competences from partners, which are needed for the project execution. In this sense, the leading question would be: *Does the RTO actively insert itself into an attractive innovation ecosystem and create strategic synergies with high-level R&D partners to expand its own field of actuation and its impact?* The following further items and operational key questions support finding an answer to it:

- Cooperation with external R&D partners: Does the RTO cooperate with external R&D partners to create interdisciplinary synergies and develop new technologies & applications on a higher complexity level?
- Integration & usage of technologies from externals: Does the RTO actually integrate and use technologies or solutions from partners or technological service providers in its own R&D projects?
- National / international players as new partners: Is the RTO aware of national and international players in relevant technology fields and strategically pursuing new attractive partnerships?

3.1.2 Technological maturity model

For the assessment of the dimensions, a technological maturity model is developed, which consists of different levels. It forms the basis for the evaluation of an RTO within the scope of the technology audit. The spectrum comprises various gradations between minimal technological maturity and very high technological maturity. Each level is described individually and specifically for each of the assessment dimensions in order to ensure the highest possible degree of standardization and thus a high degree of comparability between different RTOs.

After the technology auditor analyzed the different service areas of the RTO by deeply analyzing several R&D projects, technological equipment and research competences, the expert needs to assess the technological maturity of the RTO for each dimension and, if necessary, for each service area. For the evaluation of the dimensions, a Likert-scale is used. The purpose of its application is to give the auditor's subjective discretionary judgments greater accuracy. This is done with the help of a uniform and systematic procedure. (Likert 1932; Neukirch, Semmler 2011)

Therefore, a generic technological maturity model has been created, which consists of 5 different levels, starting with maturity level 1 – minimal technological maturity – and ending with the highest maturity level 5 – very high technological maturity.

The generic technological maturity model is visualized in the following figure.

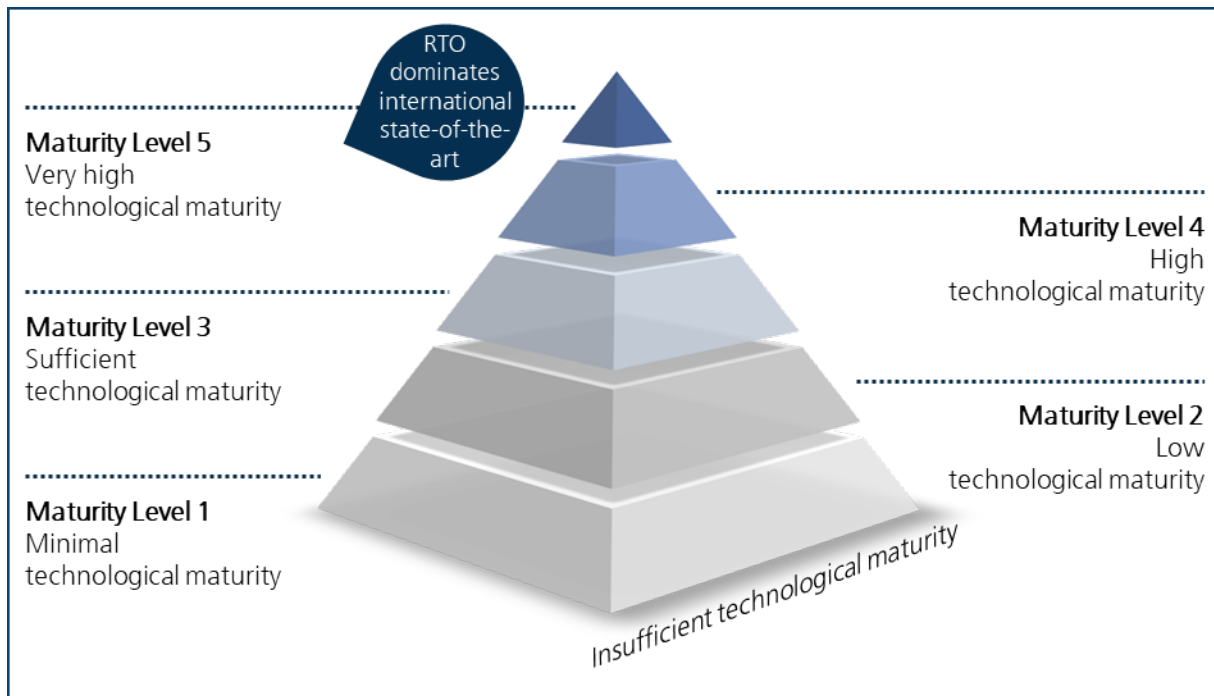


Figure 4: Technology maturity model

If an RTO reaches the technological maturity level 3, which means, that the technological maturity is sufficient, the organization is considered operational with all the necessary technologies, equipment, research competences and strategic technological partnerships to execute R&D projects in its defined service areas. If an RTO reaches a technological maturity level of 4 or higher, it means it is already very mature and is able to execute complex R&D projects and develop very innovative technological solutions.

As the generic model needs to be detailed for each of the three assessment dimensions, the following table explains the operationalized technological maturity level for each dimension.

Table 1: Technological maturity levels of all three Dimensions

Maturity Level	Dimension Technological Capability	Dimension Product & Services	Dimension Cooperation
Level 1	The RTO has basic knowledge & basic equipment for its defined technology fields. There are no strategies for further development of the technological capability existent.	The RTO started executing first basic R&D projects to deliver potential new technological solutions, products and services. There are no strategies for further development of products & services existent.	The RTO has few technological partnerships and low achievements of the organization's goals were made through cooperation. There are no strategies for further development of the cooperation with strategic technological partners existent.
Level 2	The RTO has some knowledge & first experiences in executing R&D projects as well as the basically necessary scientific equipment for its defined technology field. A basic plan for further development of its technological capability exists.	The RTO is executing R&D projects of low complexity to deliver potential new technological solutions, products and services. A basic plan for further development of products & services exists.	The RTO has some technological partnerships and some achievements of the organization's goals were made through cooperation. A basic plan for further development of the cooperation with strategic technological partners exists.
Level 3	The RTO has all main competences & scientific equipment to master R&D projects of medium complexity in its defined technology field. A systematic plan for further development of its technological capability exists.	The RTO is executing R&D projects of medium complexity to deliver potential new technological solutions, products and services. A systematic plan for further development of products & services exists.	The RTO has good technological partnerships and good achievements of the organization's goals were made through cooperation. A systematic plan for further development of the cooperation with strategic technological partners exists.

Maturity Level	Dimension Technological Capability	Dimension Product & Services	Dimension Cooperation
Level 4	The RTO has broad competences & scientific equipment to cover its entire defined R&D service portfolio on a high-quality level . The RTO is able to master R&D projects of high complexity to fulfil all requirements of current industrial demand. A systematic plan for further development of its technological capability exists and is followed ambitiously .	The RTO is executing R&D projects of high complexity to deliver and transform state-of-the-art technologies into new technological solutions, products and services . A systematic plan for further development of products & services exists and is followed ambitiously .	The RTO has very valuable technological partnerships and very good achievements of the organization's goals were made through cooperation. A systematic plan for further development of the cooperation with strategic technological partners exists and is followed ambitiously .
Level 5	The RTO has competences on international state-of-the-art level & innovative scientific equipment and is specialized in specific focal areas . The RTO is recognized as a national reference to master high complexity R&D projects and go beyond the requirements of current industrial demand . A sophisticate strategy with clear goals for further development of its technological capability exists and is followed ambitiously .	The RTO is executing innovative R&D projects of high complexity to deliver and transform state-of-the-art technologies into new technological solutions, products & services in specific focal areas . The RTO is recognized as a national reference to deliver products & services beyond the requirements of current industrial demand . A sophisticated strategy with clear goals for further development of products & services exists and is followed ambitiously .	The RTO has outstanding national and international technological partnerships and high achievements of the organization's goals were made through cooperation. A sophisticated strategy with clear goals for further development of the national and international cooperation with strategic technological partners exists and is followed ambitiously .

When analyzing and assessing the technological maturity of the RTO, the definitions in the above-mentioned table help the technology auditor to choose the most suitable technological maturity level of each assessment dimension. If the different service areas of the RTO are too distinct, it is also possible to define maturity levels not only for each assessment dimension, but also for every single service area. As this leads to a big number of maturity levels, it is advised to cluster the assessment of service areas with a similar technical maturity level.

3.2 Tools and templates

Further important elements of the technology audit methodology are the tools and templates that are used along the process. In the following chapter all available tools and templates are described briefly.

3.2.1 Procedure guide book

A guide book is available as the most important orientation for the technology auditor to assist the execution of the technology audit. This guide book contains explanations and assistance on how to proceed. This clear guideline additionally ensures that different auditors are able to proceed in a standardized manner.

3.2.2 Checklist for preparation

Since the auditor needs a lot of information to perform the technology audit, a checklist that contains an overview of all information the RTO needs to provide in preparation for the technology audit is made available. Documents such as presentations and reports, photos and videos are also part of the checklist. This list makes it possible to have all the required information available for the audit workshop in order to carry out a detailed analysis and evaluation.

3.2.3 Questionnaire for evaluation

Based on the assessment dimensions and the assessment elements, a questionnaire is available in which all assessment dimensions and items are gathered in key questions. This questionnaire is handed to the auditor and is used during the audit as a basis for structured analysis and assessment. Serving as a guideline, the questionnaire allows the auditor to record notes and to make initial assessments of the dimensions.

3.2.4 Evaluation tool

The excel assessment tool contains all assessment elements of the assessment dimensions and enables the structured and systematic assessment of the RTO by the auditor. Logical and automatic links facilitate the

recording and evaluation. Based on the evaluation results, graphics and diagrams that clearly present the evaluation results are created automatically by the tool.

3.2.5 Technology audit report

The technology audit report comprehensively summarizes all the results of the audit. There is a template available for the technology audit report. The main statements of the report are presented as briefly as possible in a summary. Furthermore, the current state of the art of the technology area in which the RTO is active is described. This is used as a basis for the benchmark of the RTO. The analysis results and assessments are described as the status-quo of the RTO and thus represent the current state. By means of a gap analysis, it is possible to identify and describe the potential for improvement in a further part within the report. Finally, recommendations are given on how the identified gaps can be closed in the best possible way and how an improvement in technological maturity can be achieved.

3.2.6 Questionnaire for the evaluation of the auditor

After completion of the technology audit, the assessed RTO has the opportunity to provide feedback on the technology auditor. A standardized questionnaire is available for this purpose. By collecting feedback, the auditor is able to continuously improve the quality of the audit. At the same time, the RTO has the possibility to name points of criticism regarding the audit process or the auditor himself.

4. Summary & Outlook

The technology audit methodology as a procedure to analyze and assess the technological maturity, which has been described in this paper, forms the essence of a long-term research work of the authors. The technology audit builds on various conceptual elements as well as tools and templates and is in this sense practically oriented. It can be applied by experienced researchers, who act as the technology auditor to assess RTOs. In the past years this methodology has been constantly revised and updated according to the key findings that resulted from the application of this methodology since 2017. However, several updates are foreseen in the future as the technology audit will further be applied to assess RTOs in the upcoming years and further research will be conducted.

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