Assessment Dimensions and Items for the Evaluation of the Technological Maturity of Applied R&D Organizations

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Abstract: Applied research and development (R&D) organizations 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 when 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. In this context, the main aim of this paper is to describe crucial assessment dimensions and the respective items within those dimensions. Therefore, it must be focused on the technology basis of the applied R&D organization to identify important evaluation items. The technological base serves as input, as both technologies and competencies that are used for the execution of R&D activities need to be analyzed and evaluated. Additionally, the results of the R&D activities need to be focused as outputs. In this regard, technologies that result in products or technological services need to be considered. Lastly, assessment items in the field of cooperation must be taken into account as technological synergies through partnerships are important success factors for R&D organizations. In this context, partners who support the execution of R&D activities must be focused.

Keywords: assessment dimensions & items, technological capability, technological resources, technological competences, technology evaluation, strategic technology management, research and technology organizations

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 research work 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. It has been developed through a series of papers over time. This paper provides a detailed analysis of crucial assessment dimensions and assessment elements. Additionally, a brief overview of the methodology itself and is the condensed outcome of previous research work is given. 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; Hecklau et al. 2022). These papers take into consideration a large number of literature and expert discussions, which are highlighted in the respective papers in detail.

2. Method of technology audit

The technological performance of RTOs and thus its technological maturity 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. 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. (Hecklau et al. 2022)

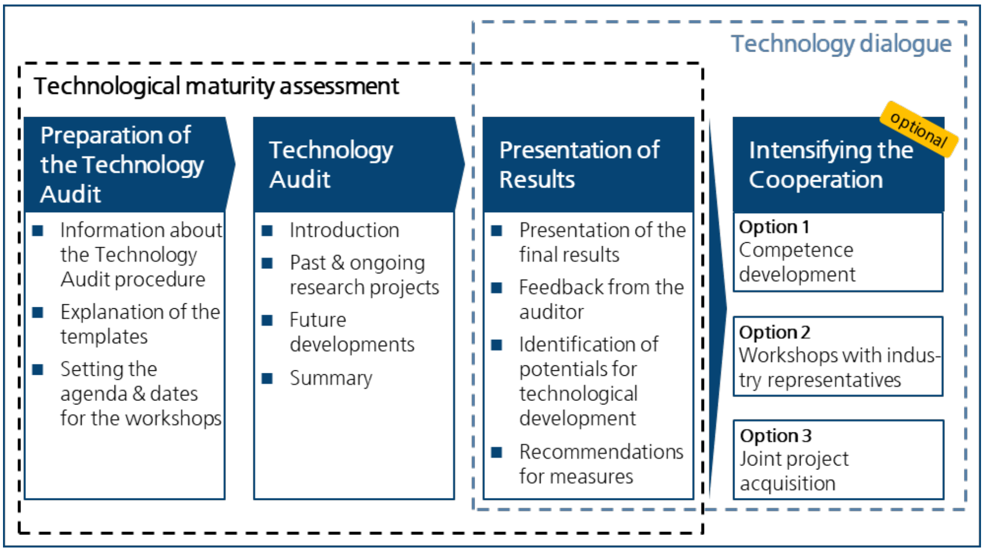

Figure 1: Technology audit procedure

The procedure consists of two main parts: the *technological maturity assessment* as well as the *technology dialogue*. The *technology audit* workshop as the main session takes place in the technological maturity assessment process step. In this step, the technological maturity of the RTO will be assessed using the assessment dimensions and assessment elements, that are focused and described in detail in this paper. Further steps are the *preparatory session* and the *final presentation and discussion of the auditor's assessment results*. In the second and optional part of the *technology dialog* the aim 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. (Hecklau et al. 2022)

3. Assessment dimensions and assessment elements

Within the procedure as briefly described above, three main technological assessment dimensions and the respective assessment items form the basis within the technology audit workshop. These dimensions target the RTO's *technology base*, *products and services*, and *collaboration*. Within the assessment dimensions, further assessment items are defined and will be described in detail in this chapter. These concretize the dimension and enable a targeted assessment within 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. (Hecklau et al. 2022) The three main dimensions are shown in the figure below.

In the following chapter, the three dimensions will be further explained and operationalized. The selected assessment items as well as the aspects and descriptions are based on an extensive literature review that include the following sources: (Garcia-Arreola 1996; Kaiser 2001; Hecklau et al. 2018; Phaal et al. 2004; Prahalad and Hamel 1990; Herstatt and Lettl 2001; Martinez-Vela 2016; Oberhagemann 2015; Sun and Fan 2016; Geisler 1999; Phaal et al. 2001; Kohl 2003; Coombs and Bierly 2006; Labuschagne and Brent 2006; Rush et al. 2007; Lau et al. 2010; Chen and Zhao 2012; Macchi and Fumagalli 2013; Liu and Jiang 2016; Chakravarty et al. 2013; Zhou et al. 2016; Gökalp et al. 2007; Ravichandran 2017; Lee et al. 2018; Salisu and Abu Bakar 2020; Wu et al. 2020; Hassan et al. 2021)

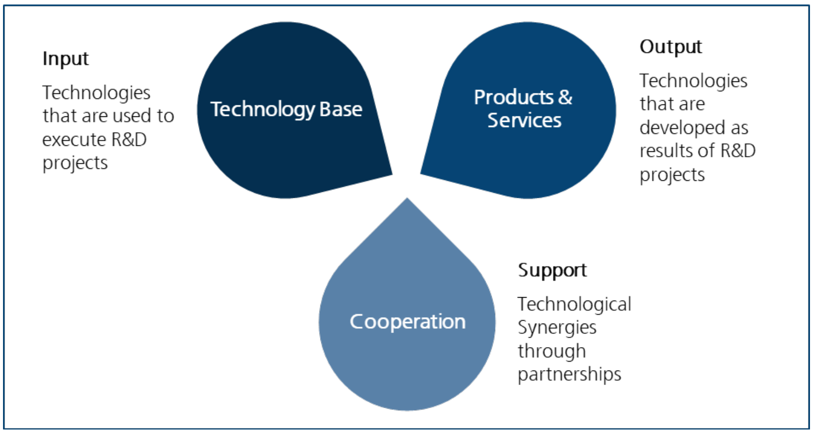

Figure 2: Dimensions of the technology audit

The essence of the literature review is described in the following chapters 3.1, 3.2. and 3.3.

3.1 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, it can be described as the input dimension. The leading question for assessing this dimension can be formulated as follows: *Is the technology base of the RTO sufficient to be able to execute R&D projects in the 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?

To detail and operationalize the raised leading key questions a set of assessment items with various aspects have been identified and will be described in the following table.

Table 1: Assessment items of the assessment dimension "technology base"

Assessment Item	Aspect	Description
	Technology Base	
Technology Strategy	Technical Resource Planning	Effective and efficient planning of technology resources are essential to the RTO’s performance and the ability to execute high-quality R&D work.
	Human Resource Planning	Human resource planning includes effective recruitment, human resource development and retention management within the RTO.
	Technology Benchmarking	Suitable technology benchmarking enables the comparison to state-of-the-art technology and thus the derivation of the technological maturity. Additionally, it allows the optimization of the own technology base.
	Technology Foresight	The look into the future and the identification of potential new relevant technologies form the basis for innovation research and builds the basis for a long-term technology strategy.
	Technology Roadmapping (external)	External technology roadmapping enables the RTO to plan strategically the integration of needed technologies into the own infrastructure in a long-term perspective by anticipating possible developments in markets, products and technologies.
	Awareness of new usable Technologies	The constant awareness of new usable technologies besides the very structure approaches of technology foresight and technology roadmapping is an important part of the mindset and thus a crucial factor for an RTO's competitiveness.
Technical Infrastructure	Building(s)	Building in which the RTO operates. It contains all rooms, such as laboratories and offices and the technical networking of the rooms.

Assessment Item	Aspect	Description
	Laboratories	All premises in which technical equipment is provided and operated. Laboratories are used for technical work such as tests, experiments or measurements.
	Maintenance of Infrastructure	The technical infrastructure, such as buildings and laboratories located therein, must be maintained and serviced in order to be functional in the long term.
	Accreditation	For certain activities, it is necessary to have laboratories or entire buildings certified and / or accredited according to certain standards in order to obtain an operating license. These include certified clean rooms, for example.
Technical Equipment / Software	General Equipment / Software	All basic equipment as well as technologies and software that are available and required to fulfill the services offered are considered here. These are standard equipment and standard software that are mandatory.
	Specific Main Equipment / Software	All specific equipment as well as highly specialized technologies and special software that are available and required to fulfill the services offered are considered here. This involves special equipment and special software that goes well beyond standard existing equipment.
	Maintenance of Equipment / Software	The existing general and specific main equipment must be maintained and serviced in order to be available in the long term as a resource for performing research services and developing products. Software must also be updated regularly and replaced by the latest versions to be functional in the long run.
Competences	General Technical Competences	A competence describes the ability to apply knowledge and skills in a targeted manner. General technical competences that are necessary to carry out research services and to develop products are taken into account here.
	Specific Technical Competences	A competence describes the ability to apply knowledge and skills in a targeted manner. A competence describes the ability to apply knowledge and skills in a targeted manner. This aspect takes into account the specific technical competences required to perform research services and develop products.
	Core Competences	The technological core competences represent bundles of technologies and capabilities with a concrete application reference (technological competences) which, detached from concrete product and market constellations, lead to a decisive competitive advantage through superior customer benefits. Core competences should be valuable, rare, difficult for competitors to imitate and not substitutable by other competences.
	Formal Qualification of Staff	The various competence areas of employees can partly be described based on formal qualifications, such as professional degrees, certifications etc., which are considered here.
	Competence Development / Training	The RTO can proactively contribute to the employee competence development by providing internal or external trainings and education. This builds the basis for the necessary qualification level of the human resources for today and the future.

3.2 Products and 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, it can be described as the output dimension. The leading question is the following: *Is the RTO actually transforming technologies into innovative applications / products with a clear benefit for the industry by executing R&D projects in the defined R&D / service areas?* The following items and operational key questions help to guide the technological maturity assessment:

- Execution of R&D projects: Is the RTO 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 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?

The following table describes the main assessment items and the respective aspects of the assessment dimension of *products & services*.

Table 2: Assessment items of the assessment dimension "products & services"

Assessment Item	Aspect	Description
Products & Services		
Complexity of R&D&I Results	Market-Pull / Technology Push	Market-Pull refers to a customer-driven product innovation. Conversely, Technology Push refers to a new technology or a new application of a technology that provides an innovation or problem solution on the market.
	Diversification according to TRL	Technology readiness levels (TRL) are used to classify the range of conducted research activities between basic research, applied research and commercialization. Within an RTO various TRL level should be addressed to diversify the research activities.
	Multidisciplinarity	Multidisciplinarity describes the number and diversity of scientific disciplines engaged in research activities of the RTO.
	Project Volume	Complex research projects need an adequate financial volume in order to have the chance to create complex and innovative research results.
	Run Time of the Project	Longer projects allow more complex research activities and thus can lead to more complex research results in the defined duration of the project.
	Follow-Up Projects	All projects that follow on from the completed project and possibly build on it in terms of content allow the creation of more complex research results.
Innovative Technological Results	High Quality Products / Processes	A high technological maturity lead to a high quality of the products and processes offered by the RTO, in particular in regards to the clear benefit for the industry.
	High Quality Technical Services	A high technological maturity lead to a high quality of the technical services provided by the RTO, in particular in regards to the clear benefit for the industry.
	Customized Technical Solutions	Innovative technological results can also be described by the extent to which the RTO is able to offer customer-specific technical solutions. This aspect takes into account how complex and individual requirements can be addressed.
	High-Quality Research Work	A high-quality research work of the RTO builds the basis for successful creation of innovative technological solutions.
	Technology Protection / IP	Protecting its own technologies through effective IP management is a crucial factor for the RTO to ensure long-term competitiveness. As intangible technological resources, patents and licenses are a central dimension of this.
New Technological Solutions as Products	Technology Trends	The innovativeness of technologies can only be considered in the context of global technology trends, that indicate which technologies are currently formative and will be in the future as potential new products of the RTO.
	Technology Scouting	Effective technology scouting is essential to identify technology trends and innovative technologies at an early stage. The RTO can thus position itself accordingly to be able to develop state-of-the-art technologies as products itself.
	Technology Roadmapping (internal)	Roadmapping internal technology developments enables the RTO to plan strategically and for the long term by working out the expected future developments of the own technological solutions as products.
	Potential Technology Spillovers	Technology spillover refers to the unintentional technological benefits of and to the RTO that result from the research and development efforts of the RTO and other companies without sharing the costs. The RTO can thus benefit from transmission effects to create new technological solutions as a product.

3.3 Cooperation

In the *cooperation* dimension, the level of integration of the RTO within the regional, national, or even international innovation ecosystem is analyzed and assessed. Synergetic technological cooperation helps the RTO to get access to complementary research competences or even technologies, equipment and infrastructure from partners, which are needed for the research work. In this sense, this dimension can be described as the support dimension and focusses on the following leading question: *Does the RTO actively insert itself into an attractive innovation ecosystem and create strategic technological synergies with high-level R&D partners to expand its own field of actuation?* 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 technological synergies and develop new technologies & applications on a higher complexity level?
- Integration & usage of technologies from externals: Does the RTO 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?

In the following table the raised leading key questions will be described in detail and operationalized with a set of assessment items with various aspects.

Table 3: Assessment items of the assessment dimension "cooperation"

Assessment Item	Aspect	Description
Cooperation		
Cooperation with External research organizations	Universities	Collaborations with universities and other educational institutions with the aim of jointly providing research results and developing innovative solutions are taken into account in this aspect.
	Research Academies	Research academies as well as scientific working groups can support the activities of the RTO as external cooperation partners. Cooperation with research academies is considered in this aspect.
	RTOs	To provide joint research performances and develop innovative solutions, synergistic collaboration with other RTOs is considered in this aspect.
Cooperation to Subcontractors / Third Parties	Integration & Usage of Technologies from Service Providers	If the technological basis for carrying out research services is not fully available in the RTO, recourse can be made to service providers who make technologies or technological services available. This collaboration for the use and integration of third-party technologies and services are considered in this aspect.
	Integration & Usage of Technologies from Customers	In collaborative applied research projects, it may be possible to leverage end-user technologies and technology services that are needed to deliver or accelerate the targeted research performance. This aspect also focuses on an incomplete technology base of the RTO that necessitates the involvement of partners for service provision.
Cooperation with Innovation Ecosystem	Start-Ups	Cooperation with smaller and young companies / start-ups can be advantageous for the RTO for its own service provision. Innovative and agile start-ups can, for example, close competence gaps of the RTO or support the rapid creation of prototypes.
	Incubators	Incubators can be helpful as cooperation partners for the RTO for further networking with start-ups and young companies. For example, new and innovative ideas from start-ups can be pursued together with the RTO and initiated and supported by incubators.
	Accelerators	Cooperation with accelerators can be advantageous for the RTO's service provision. Accelerators support start-ups, particularly in the early phase, for example by providing coaching or financial resources and by establishing the necessary contacts. RTOs can benefit from start-ups supported by accelerators or can profit from the accelerator's extensive network of experts.

Assessment Item	Aspect	Description
	Science and Technology Parks	RTOs can be a part of a science and technology park, which often results in close collaborations simply because of the physical proximity to other organizations in the park (e.g., industrial companies, other research organizations). However, cooperation can also be beneficial for RTOs that are not part of a science and technology park to work with spatially clustered partners.
Future Cooperation with National / International Partners	Partner Scouting	For future activities of the RTO it is necessary to be able to identify important and potential new partners. Partner scouting aims at the structured observation of current partners as well as the early identification of potential partners that may be important for the service provision of the RTO.
	Competitor Analysis	Competitors can also be interesting as partners for the RTO. There is also a risk that partners may become competitors. Therefore, the focus must be on current and potential competitors that may be relevant for future collaborations.

The above described assessment dimensions and the respective assessment items build the basis for the assessment of the technological maturity of RTOs.

4. Technological maturity model

For the evaluation of the assessment dimensions and the assessment items, a technological maturity model is developed, which consists of different levels. It forms the basis for the assessment of an RTO within the scope of the technology audit, where each of the assessment dimensions and items will be evaluated according to this model. 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. (Hecklau et al. 2022)
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; Hecklau et al. 2022)

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.

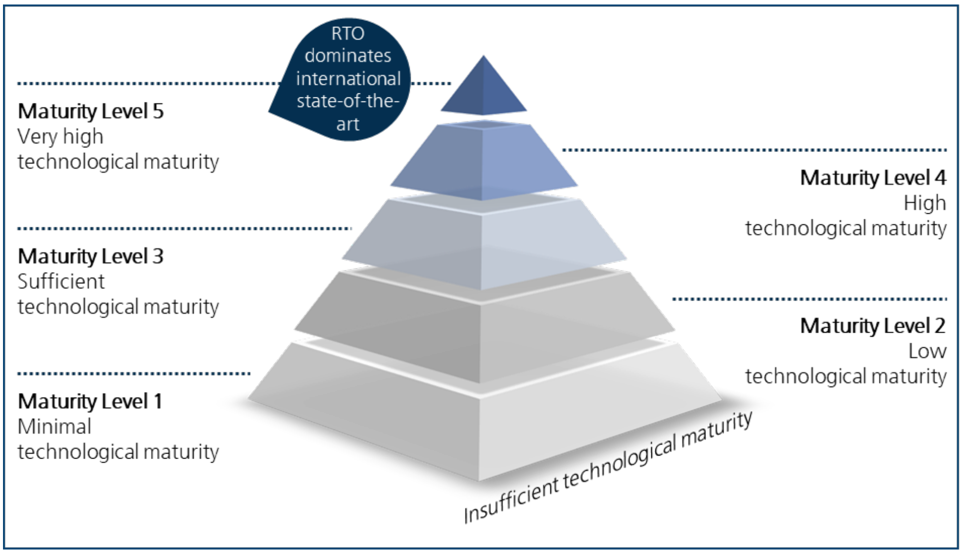

Figure 3: Technology maturity model

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. 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 and item, 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.

5. Summary and outlook

The technology audit methodology as a procedure to analyze and assess the technological maturity forms the essence of a long-term research work of the authors. In addition to a maturity model, various checklists, templates, etc., the assessment items form the basis for the evaluation of technological maturity. Therefore, the described assessment dimensions and the respective assessment items have been identified and analyzed in detail.

As the technology audit is practically oriented, the high number of assessment items is not practical. That is why, in a next step a questionnaire will be created and distributed to several experts (e.g. methodology expert, technology experts) to assess the relevance of the assessment items. The main goal is to reduce the number of assessment items to an essential minimum. All remaining assessment items will be considered as additional elements.

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