# A Harmonized Approach for Constructing a Robust and Efficient Technology Backbone for Agile Manufacturing Systems

Olga Meyer, Greg Rauhoeft, Christian Henkel
Fraunhofer Institute for Manufacturing Engineering and Automation IPA
Stuttgart, Germany
Email: {olga.meyer, greg.rauhoeft, christian.henkel}@ipa.fraunhofer.de

Ambra Calà
Otto-v.-Guericke University
Magdeburg, Germany
Email: ambra.cala@ovgu.de

***Abstract*—To quickly satisfy customer needs and to respond to market changes it is eminent to develop agile manufacturing systems. These have to support integration of flexible and reconfigurable production systems as well as IT technologies across the entire value chain. While implementing advanced technologies or integrating these into new system solutions, manufacturers and system developers have to understand the current and the desired technological capabilities of the system application. Before constructing a robust technology backbone for agile manufacturing systems, it is therefore important to make a clear picture of existing standardized solutions. Though a vast variety of assessment techniques is presented in literature, it is still unclear which approach is appropriate for a technology gap analysis, especially when developing agile manufacturing system solutions. Therefore, the harmonization of assessment techniques is essential for the analysis of the technological compliance among various systems. This paper presents a harmonized approach with exemplary results in order to navigate system developers and stakeholders towards effective and robust technology solutions that are compliant with Industry 4.0 goals and independent of manufacturing application fields.**

***Index Terms*—harmonized, gap analysis, assessment criteria, technology backbone, agile manufacturing, flexible and reconfigurable production systems, Industry 4.0.***

## I. Introduction

In the present day, while aiming to achieve differentiation and a competitive advantage on the industrial market, production and manufacturing companies are facing several challenges characterized by constantly changing market requirements, demand of new business models or product specifications, rising labor costs, and the introduction of advanced technologies. On the one hand, investing in new promising features and technological innovations that are compliant with Industry 4.0 goals can bring a company concrete advantages, e.g. converting simple process management solutions to advanced migration strategies of the whole company. On the other hand, companies experience difficulties developing know-how for the majority of Industry 4.0 topics [1]. Furthermore, rapidly changing market requirements meet slow and insufficient adaptability of manufacturing systems. This fact leaves organizations reacting to the market instead of becoming pro-active [2].

The newly developed systems, which are known as cyber-physical systems (CPS), are now able to collaborate through advanced interoperability technologies, such as the industrial middleware [3]. CPS allows intelligent manufacturing operations where various different products use a variety of materials in different volumes while following inhomogeneous processes and collaboration patterns [4]. Using agile manufacturing techniques and being compatible with hardware and software from specific vendors, CPS are developed in strong contrast to traditional, purpose-built systems that are inflexible in their scope of application and require constant human supervision to perform their tasks.

The construction of flexible and reconfigurable CPS in production is one of the main challenges for European manufactures. Many of these challenges arise from the current trends of the Industry 4.0, such as the design of intelligent reconfigurable plug-and-produce systems [5]. Such systems are expected to re-adapt themselves during the plug and / or unplug operations and possess the so-called self-* features, e.g. self-adaptation, self-learning, and self-reconfiguration [6]–[8]. Baring great promises of being able to solve many current challenges of manufacturers, the implementation of reconfigurable plug-and-produce systems requires significant changes within the information technology (IT) infrastructure of an organization. Unfortunately, many vendors are still overstrained due to the novel nature of agile technology development. Moreover, the information on how to develop and integrate these new technologies into the existing IT architectures is incomplete and often unclear. For this reason it is crucial to investigate modern techniques that offer long-term potentials and economic efficiency in order to construct robust manufacturing IT systems and to allow competitive differentiation [9].

Minimizing conflicting and redundant standards in future IT architectures is expected to reduce system's complexity and development efforts. The main goal of the proposed

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approach is to harmonize technological know-how in industrial environment in order to reduce costs of complying with future standards for upcoming hardware and software developments. Moreover, this approach aims to synchronize existing methodologies as well as standard solutions across various manufacturing application domains. Additionally, the developed methods aim to provide efficient techniques, principles and concrete steps for a technology gap analysis and to support system developers and stakeholders in choosing applicable methodologies for the analysis of the technological situation within their own organization.

The harmonized approach was initially developed in the EU HORIZON2020 project PERFoRM (Production harmonizEd Reconfiguration of Flexible Robots and Machinery) [10], which aims to develop the next generation of agile manufacturing systems that are dynamically reconfigurable and can react to rapid changes of market conditions. Based on modular plug-and-produce components with built-in intelligence, such systems will be able to flexibly adopt new features and functionalities proposed by the diverse emerging technologies. For this purpose, a distributed control architecture was defined during the PERFoRM project. This architecture enables the integration of production applications and components through a service-oriented middleware, compliant with Industry 4.0 paradigm [11]. To validate the project goals for different kinds of industry needs, PERFoRM is investigating four industrial use cases (i.e. production lines for: compressors, automobiles, home appliances and aerospace) that utilize a wide range of manufacturing system technologies, products and production processes.

In order to overcome existing barriers for the European industry and to avoid the development of redundant concepts PERFoRM targets to agree on a clear technology stack with both technology providers and technology consumers [12]. Thus, a crucial part of the innovation work that has been currently addressed in the PERFoRM project was the definition, specification and prototype implementation of a reference architecture, including standard connectivity interface technologies [3]. For this reason, PERFoRM applied this harmonized approach in order to evaluate and select the best available technologies and to close possible gaps in the defined IT stack. Based on the techniques of this approach, PERFoRM was able to make recommendations and create guidelines for the system developers on how to select the appropriate technologies addressing such important features as their implementation, integration, deployment efforts, technology availability, robustness, and maturity.

The exemplary results presented in this document are based on real data collected during the PERFoRM technology gap analysis.

## II. Related Works and Approaches

During the research we came across very few related works and existing methodologies for a technology gap analysis. In management literature a gap analysis is reduced to a comparison of company's required performance level and their current performance, whereas the main goal is the identification of gaps to reach the desired performance [13]. However, we want to focus on the technology gap analysis including not only performance but also many other important factors, such as the maturity of the technologies or their availability, with identified gaps to be filled by adopting a certain technology in the company's IT architecture.

Yusuf et al. identify a set of attributes and concepts of agile manufacturing, along with challenges that may occur in the implementation that must be addressed in the construction of a technology backbone for agile manufacturing systems. The described concepts primarily revolve around the sharing and generating of knowledge and competence to enhance the capabilities of an organization, the ability to perform ad-hoc cooperation within and beyond the organization, along with the ability for operational reconfiguration [2].

A more general approach is provided by Gerald J. Balm [14]. He describes a method of comparing one's own enterprise to similar enterprises to gain insights into possible improvements that can be made to the position of an organisation within the market. Improvements should always be aimed at surpassing the current state of a given benchmark in order to prevent the method of being reactive. Furthermore, Balm suggests the use of questionnaires with a scale of satisfaction sent to relevant entities to gauge the current state of the organisation for benchmarking.

Unfortunately, neither [2] nor [14] present a profound and harmonized gap analysis methodology that addresses the selection of best available technologies for agile manufacturing systems in practice.

Another approach towards technology gap analysis is presented by Battese et al. [15]. They propose using a metafrontier approach based on a stochastic method to enable comparisons across different companies and to precisely analyze the gathered data. Nevertheless, such stochastic techniques are difficult to apply to the choice presented by diverse hypothetical heterogeneous technologies, which at the same time yield a wide range of dependencies.

One of the most accessible approaches for a technology analysis is presented by Silvia Rummel [9]. The procedure is based on object-related proof of capability using qualitative and quantitative evaluation methods. Rummel claims that the procedure is well suited for the decomposition of the technology-driven concepts and outlines a set of steps to correctly assess the technological maturity. However, the approach shows deficits in terms of robustness and construction of a technology backbone. Additionally, Rummel's approach does not maintain harmonization requirements. In particular, the integration of standardized technologies does not focus on know-how and experience gathered from other successful projects. That is why our harmonized approach only references the stages of the development method proposed in [9] and develops new methods in order to integrate harmonized techniques and fulfill the technology gap analysis as described in the next sections.

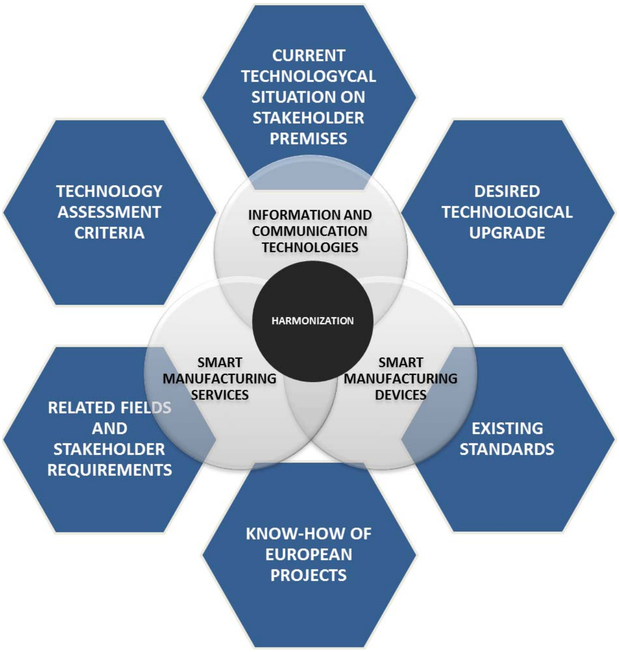


Fig. 1. Levels of harmonization activities.

## III. Harmonized Approach and Application Levels

One of the main goals when constructing a robust and efficient technology backbone based on agile concepts is to reach a high degree of compliance among various heterogeneous production systems and technologies. However, in order to extract common information objectives from diverse data sources, various specific application fields need to be addressed. For this purpose, we identified two key levels of the harmonization activities addressed in our research as shown in Fig.1: the executive level (outer level) and the technology level (inner level) of harmonization.

The *executive level* focuses on the harmonization of assessment methodologies in several research fields, such as existing standards, academic know-how, as well as approaches dealing with various evaluation measures and criteria. These fields cover expert knowledge that is acquired from academic sources. Unfortunately, these are the most common few fields referred to by previous works and approaches so far. To establish a precise scope of information gaps it is important to include other relevant non-standard sources, which can also provide up-to-date information and share "lessons learned". Therefore, within this research we specifically took into consideration the know-how of other European projects and expert knowledge for the analysis of current technological achievements. Finally, we come to the conclusion that only a combination of multiple research fields at the executive level, such as academic knowledge and practical experience collected from external and internal sources, can guarantee a reasonable background for an ubiquitous approach to assess new technologies.

Another important area of focus, next to the assessment methodologies and their techniques, is the *technology level*. Since agile manufacturing requires the use of technologies that can be rapidly adapted and reconfigured without applying much efforts [16], this level aims at harmonizing numerous data retrieved from the technology survey to support flexibility and reconfigurability of adapted systems and minimize possible hardware and software changes. Accordingly, the collected technologies can be broadly divided in to three general application fields:

1) technologies related to the information and communication field (e.g. communication protocols and various interface technologies);
2) technologies enabling smart manufacturing services (e.g. software applications of diverse production processes); and,
3) technologies describing smart manufacturing devices (e.g. sensors, robots, various manufacturing equipment, etc.).

In practice, the presented harmonized approach can be executed in six successive steps [17]. However, this paper does not intend to describe the steps but rather to provide supplementary techniques, as well as useful templates to support the gap analysis process.

## IV. Harmonization Techniques ans Assessment Tools

This section describes the techniques and tools used to collect information about the current technological situation under the premises of project use cases and the know-how of the consortium. The approach also contains methods to evaluate the collected information according to pre-defined assessment criteria.

### A. *Case Study and Know-How Survey*

The first step of the harmonization approach is to analyze the stakeholders' case studies and to identify the relevant objectives of the survey. These objectives are supposed to clarify what particular technologies are of interest and which should be focused on in future. First, during several interviews with stakeholders, diverse technical requirements have to be collected. Before the interviews, it is recommended to prepare a simple beginner's guideline with an initial list of possible technologies that could be related to the case studies. The stakeholders can either select the required technologies from the list or extend this one with additional information.

### B. *Technology Assessment Criteria*

The technology assessment criteria are used to supplement the assessment methodologies and offer discrete measurement techniques to verify the compliance of the technologies with advanced industrial requirements. During our preliminary research we developed a set of eleven assessment criteria, which can also be found in TABLE I. These criteria are based on the Partovi's strategic evaluation methodology for manufacturing technologies [18] and are used to describe each technology regarding its full range of essential characteristics that cover strategic focuses driving competitive advantage, value chain activities, and characteristics of available technologies.

TABLE I
TECHNOLOGY QUESTIONNAIRE

| | |
|---|---|
| **Stakeholder** | |
| **Technology Group** | |
| **Technology Name** | |
| **Short Description** | |
| 1. **Manufacturing Usability Level** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |
| 2. **Level of Maturity & Readiness** | |
| a. Advanced (Test & Launch) | ☐ |
| b. Medium (Prototype) | ☐ |
| c. Low (Research) | ☐ |
| d. None / No answer | ☐ |
| 3. **Level of Automation** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |
| 4. **Technological Integrity Level** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |
| 5. **Economic Benefit** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |
| 6. **Substitution Level** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |
| 7. **Market Availability & Technology Support Level** | |
| a. Very common | ☐ |
| b. Limited | ☐ |
| c. None / No answer | ☐ |
| 8. **Future Market Potentials** | |
| a. Advanced (75 − 100 %) | ☐ |
| b. Medium (50 − 75 %) | ☐ |
| c. Low (25 − 50 %) | ☐ |
| d. Insignificant / No answer (0 − 25 %) | ☐ |
| 9. **Robustness & Susceptibility Degree** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |
| 10. **Security Status** | |
| a. High | ☐ |
| b. Low | ☐ |
| c. Insecure / No answer | ☐ |
| 11. **Industry 4.0 Relevance** | |
| a. Advanced | ☐ |
| b. Medium | ☐ |
| c. Low | ☐ |
| d. None / No answer | ☐ |

| Technology / Technology group name | Average score (A) | Questionnaire (q) | Project (P) | Current (CU) Desired (DE) | Usability | Maturity | Automation | Integrity | Benefit | Substitution | Availability | Potential | Robustness | Security | I4.0 Relevance | Single score (S) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Robot Operating Systems Technology | | | | | | | | | | | | | | | | |
| Robot motion planning (fixed robots) | 28 | 1 | P1 | **CU** | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 28 |
| | | 2 | P2 | **CU** | 2 | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 28 |
| Robot Control | 26 | 1 | P3 | **DE** | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 3 | 33 |
| | | 2 | P1 | **CU** | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 27 |
| | | 3 | P2 | **CU** | 2 | 3 | 2 | 3 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 27 |
| | | 4 | P4 | **CU** | 3 | 2 | 2 | 0 | 0 | 2 | 2 | 2 | 2 | 0 | 2 | 17 |
| Robot configuration | 26 | 1 | P1 | **DE** | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 26 |
| Automatic restart | 13 | 1 | P2 | **CU** | 1 | 2 | 1 | 1 | 1 | 2 | 2 | 1 | 1 | 0 | 1 | 13 |

Fig. 2. Snapshot of the PERFoRM Gap Analysis Matrix.

### C. Questionnaires

Questionnaires are an effective technique to collect information considering the granularity of assessment data and the particular rating details. TABLE I presents a questionnaire that is used to collect assessment data about each specific technology, during a second round of interview with stakeholders. The questionnaire is also applicable for gathering information with the focus on desired technologies in case there is a specific need communicated by a stakeholder or a know-how provider, e.g. a technology upgrade or an exchange of a specific tool. Such particular requests are usually communicated if there are explicit dependencies of described technologies, or these have to be exclusively integrated into a future system.

### D. Evaluation of Assessment Results

For the evaluation of the assessment results we composed a Gap Analysis Matrix (GAM). Fig.2 shows a snapshot of the evaluated information for the *Robot Operating System* group of technologies. Thus, the GAM comprises a number of entities across all evaluation criteria, including various maturity levels. The maturity levels are assessed for each technology and are rated according to the experience of the project's partners, stakeholders or technology experts. TABLE II shows the detailed scoring systems that were applied for the technology questionnaire presented previously.

The GAM should include only complete data sets. The estimation can be conducted in two different ways: horizontally and vertically.

The *horizontal evaluation* is based on assessment results collected in the questionnaire $q$ with $n$ assessment criteria. It includes:

1. the single score $S_q$, which is derived from the average sum of $m$ evaluation points for each of eleven evaluation criteria, whereas

$$S_q = \frac{1}{n}\sum_{x=1}^{n} m_x, \quad x = \{1 \ldots n\}; \tag{1}$$

2. as well as the average score $A$ for a technology that is assessed in $m$ various questionnaires, whereas

$$A = \frac{1}{m}\sum_{q=1}^{m} S_q, \quad q = \{1 \ldots m\}. \tag{2}$$

TABLE II
THE SCORING SYSTEM OF THE MATURITY LEVELS

| System A | | System B | |
|---|---|---|---|
| **Level** | **Score** | **Level** | **Score** |
| ***Advanced*** | 3 Points | ***High*** | 3 Points |
| ***Medium*** | 2 Points | ***Low*** | 1,5 Points |
| ***Low*** | 1 Point | ***No answer*** | 0 Points |
| ***No answer*** | 0 Points | – | – |

*A* is calculated only in case there are several questionnaires collected for one and the same technology and submitted from different sources. For example, in Fig.2 there are four various assessment results ($m$=4) collected for the technology *Robot Control* from four various sources.

To analyze the maturity level of a separate technology group a *vertical evaluation* can be conducted. It calculates the relevant share, which is measured by a technology group in comparison to the average summation of all collected points with regard to one calculated criterion. For example, Fig.3 shows a vertical evaluation for the technology group *Robot Operating System*. According to this analysis this group differentiates by a high degree of security, substitution and maturity of currently used technologies.

### *E. Gap Analysis Techniques*

To define and select the best available technologies and tools for a specific case study, the methodology includes the mapping of the collected technology scores that are required by the stakeholders and those, which were assessed by the technology experts. In order to find a matching technology, we considered three main objectives in our approach:

1) the substitution possibility of the technology assessed by a given description;
2) the maturity level of the technology provided as an average score; and, finally,
3) the relevant share of the technology including assessment criteria in comparison to overall results.

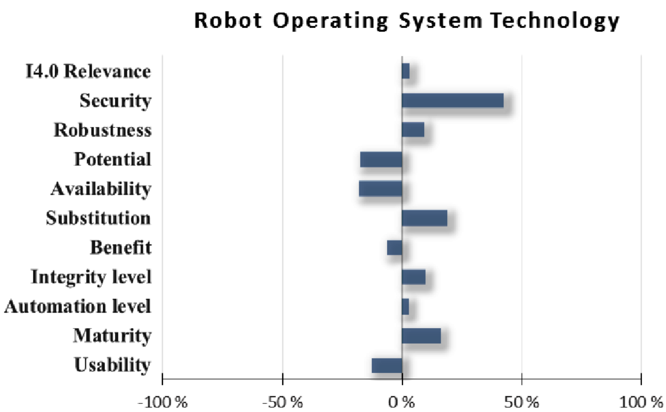


Fig. 3. Example of the PERFoRM vertical evaluation.

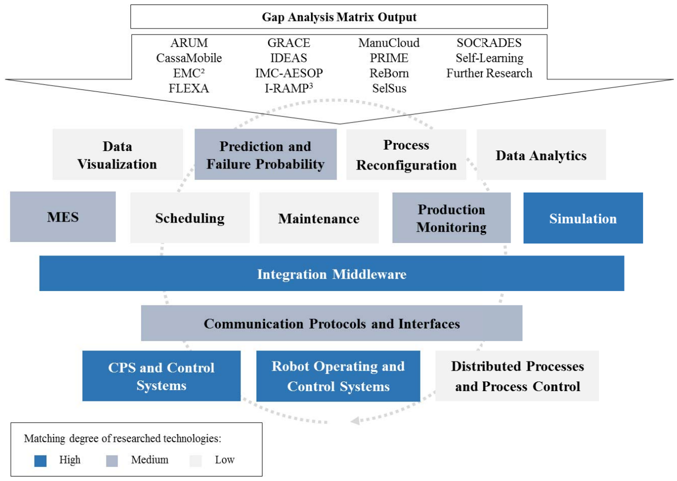


Fig. 4. Matching results of the technology gap analysis in PERFoRM.

A technology gap can be assumed only when the perfect match is missing.

To specify the matching propositions, which could contain one or more compatible technologies, we identified the matching degree for each discovered technology gap. Accordingly, we assumed a low matching degree by a combination of one or two technologies, which could not completely substitute a technology solution but have to be further developed or need additional investigation. A medium degree of compatibility was assumed for technologies that provided a partial solution and could only cover the gap to a certain degree. In case of a partial solution special attention was paid to the stakeholder proposition and technology needs. Finally, a high matching degree was applied for the technologies that were expected to provide a fully automated and integrated solution and, which could be integrated in the developed system with low efforts.

Based on the list of the identified perfect match propositions we were able to compose a summarized representation of the recognized gaps as it is shown in Fig.4. This picture compares the PERFoRM's consortium knowledge and the experience gathered during former European research projects with the PERFoRM use cases goals, with respect to the considered technologies [17]. The developed technologies of the analyzed previous projects contain different solutions that integrate robots and machinery into the operational control and logic domain. All the research projects and related technologies are listed in the picture. According to this information we could make further recommendations for the technology use in order to cover the possible gaps in the PERFoRM IT architecture.

The presented gap analysis techniques require additional skills. It is strongly recommended to deeply understand technical and non-technical requirements declared by a stakeholder as well as to recognize the technical details of each assessed technology. We also suggest to involve stakeholders and technology experts into the gap analysis process and to encourage them to comment on the findings.

## V. Further Recommended Techniques

In course of the PERFoRM gap analysis more than 200 technologies were submitted by various experts from more than 15 relevant European projects. These technologies could be analyzed according to the proposed harmonized techniques. However, in order to achieve a higher degree of harmonization, it could be recommended to consider further additional methods and possibilities.

One possibility would be to perform a general online survey to significantly increase the amount of responses. This may improve the assessment degree along with the precision of the data. However, there is no guarantee that the respondents are experts in the given fields. As a result, this may conversely decrease the overall quality of the gathered data.

Another method to handle the quality of the data would be to perform a stochastic analysis as described in [15]. However, we expect difficulties in identifying the non-expert answers and in measuring the consensus among experts.

Finally, the quality of the data can be partially improved by sending out invitations to the questionnaire only to known experts. This would enhance the quality of the collected data and ensure that the information is indeed provided by expert knowledge. But, once again, it may decrease the precision of the data since possible valuable answers from the non-experts are not considered.

Our experience in PERFoRM shows that an assessment is always a balance between quantity and quality of the data since every project deals with different specific technologies. For this reason we conclude that the expert knowledge is the more valuable weighting between the choices.

## VI. Conclusion

In this paper we presented a harmonized ubiquitous approach addressing the missing techniques and tools in assessment methodologies that are presented in literature. This approach is used to support stakeholders and system developers in minimizing possible risks in adopting new technologies when developing agile manufacturing system solutions. Specifically, the approach assists in adopting intelligent plug-and-produce components and other relevant Industry 4.0 solutions in a company's existing IT architecture and its production environment. To achieve this we provided practical guidelines based on the experience gained during the PERFoRM project in form of supplementary techniques, as well as other useful templates for a technology gap analysis.

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