Towards Industrial Exploitation of Innovative and Harmonized Production Systems

A. Calà[1], M. Foehr[1], D. Rohrmus[1], N. Weinert[1], O. Meyer[2], M. Taisch[3], F. Boschi[3], P. M. Fantini[3], P. Perlo[4], P. Petrali[5], J. Vallhagen[6]

[1] Siemens AG, Erlangen, Germany, matthias.foehr@siemens.com
[2] Fraunhofer-Institut für Produktionstechnik und Automatisierung, Stuttgart, Germany, olha.meyer@ipa.fraunhofer.de
[3] Politecnico di Milano, Milano, Italy, {marco.taisch, filippo.boschi, paola.fantini}@polimi.it
[4] Interactive Fully Electrical Vehicles SRL, Rivoli (TO), Italy, pietro.perlo@ifevs.com
[5] Whirlpool Europe SRL, Cassinetta di Biandronno (VA), Italy, pierluigi_petrali@whirlpool.com
[6] GKN Aerospace Sweden AB, Trollhättan, Sweden, johan.vallhagen@gknaerospace.com

Abstract— **Industrial competitiveness today means shorter product lifecycles, increased product variety and shorter time-to-market. To face this challenge, the manufacturing industry is forced by different initiatives, namely Internet of Things, Industrie 4.0 and Cyber-Physical System to move from traditional control approaches towards intelligent manufacturing control systems that are dynamically adaptable to changing production environment and flexible to different processing tasks. For years several emergent intelligent approaches such as Multi-Agent Systems, Service-oriented Architecture, Plug-and-Produce systems and Cloud technologies have been developed in a variety of research fields. This paper reviews the state-of-the-art methodologies and technologies of flexible and reconfigurable manufacturing systems outlining the differences between them and arising benefits within the vision of the PERFoRM (Production harmonizEd Reconfiguration of Flexible Robots and Machinery) project. Current trends and challenges in industrial implementation of these methodologies are reported and research opportunities are described.**

Keywords—cyber-physical production systems; decentralized distributed control approaches; flexible and reconfigurable production systems; agile plug and produce systems.

I. INTRODUCTION

The world economy, and naturally also the European, are facing enormous pressures to their manufacturing domain. On the client side, the demand for more customized, cheaper products with higher quality is driving the manufacturing companies to search for innovative developments to achieve those requirements. On the company side, disturbances such as delays or shortages from suppliers or resources breakdowns may have a deep impact in the company performance. Allied to those disturbances, there is the constant need for reduction of production cost. To this, it urges to develop and bring new paradigms into the manufacturing sphere, and particularly new manufacturing control systems as well as smarter manufacturing equipment exhibiting features, such as modularity, re-configurability and fault tolerance [1].

While these challenges are not new to the European market, the trend for globalization, and the pressure especially from Asian and US competitors is constantly rising. Despite the efforts already put in solving these issues by the European commission, industry and research institutes, only few have been brought successfully into industrial application. Reasons for this are varying, but may be generalized as follows. Many projects are narrowly focusing on solving highly specific problems while neglecting other technological issues. Additionally, research projects are often using non-standardized technological basis platforms or specific interfaces which are not yet applied in industry. The missing common basis is an obstacle for transferring results beyond specific pilot cases and for combining the different research solutions in order to address multiple industrial challenges.

Within the PERFoRM project, existing solutions from public and private research should be used and combined in a common platform (Middleware) in order to allow their industrial adaptation. The objective of the work presented in this paper is to describe the principles of the PERFoRM project (Section II). Section III is dedicated to the project objectives with regard to the expected benefits of the four industrial use cases within PERFoRM. In section IV, the state-of-the-art methodologies and approaches towards CPPS is presented. In section V, an overview of the activities accomplished within PERFoRM is given focusing on the following tasks: i) requirements definition, ii) human perspective analysis, and iii) technology gap investigation.

II. PERFORM MOTIVATION

The EU HORIZON 2020 project PERFoRM (Production harmonizEd Reconfiguration of Flexible Robots and Machinery) [2] is aiming at the conceptual transformation of existing production systems towards agile, networked plug-and-produce production systems in order to achieve a flexible manufacturing environment based on fast reconfiguration of machinery and robots as response to operational or business events. The next-generation production systems need to be dynamically adaptable to changing production environment, open to new features and functions, flexible to different processing tasks as well as constantly changing product variants and modular to enable quick and economical changes in the production line [1]. Lot of research has been conducted in intelligent manufacturing approaches for decades. However, the reality today still shows the dominance of lean production systems according to the Toyota principles based on traditional approaches. One disadvantage of the traditional lean shopfloor management is that the data generated by the lean methods are seldom digitally acquired and seamlessly integrated in the

shopfloor data management systems. Therefore this valuable data is not available for agile processes linkage and applications like predictive maintenance.

Previous European projects provided different individual solutions necessary to create an agile production system but none of them developed that concept in an integration-ready form. PERFoRM intends to integrate and harmonize existing research and innovation results and prepare standards to facilitate industrialization and dissemination of distributed modular approaches at device level, according to the Cyber-Physical Production Systems (CPPS) paradigm. CPPS are characterized by high collaboration and capability to share information among plug-and-produce devices, robots and machines, which requires a solid manufacturing middleware able to ensure full interoperability via open communication and standardized data exchange [3].

PERFoRM is an industry-focused project in which four real use case scenarios will validate the future flexible automation solution on the factory shopfloors. Real industrial and business impacts can be achieved by careful consideration of migration strategies and ways to transform production lines to CPPS.

III. PERFORM OBJECTIVES

The main objective of the project is to integrate and harmonize the existing methodologies in a unique solution and to validate this approach universally for different kinds of industry needs. Therefore, four industrial use cases are investigated, i.e. compressor, automotive, home appliance and aerospace, thereby covering a wide range of manufacturing systems, varying in industrial domain, product complexity, production volume and processing types.

The PERFoRM industrial use cases will take several advantages in adopting flexible and reconfigurable solutions based on CPPS, albeit they have diverse goals due to the different nature of their products.
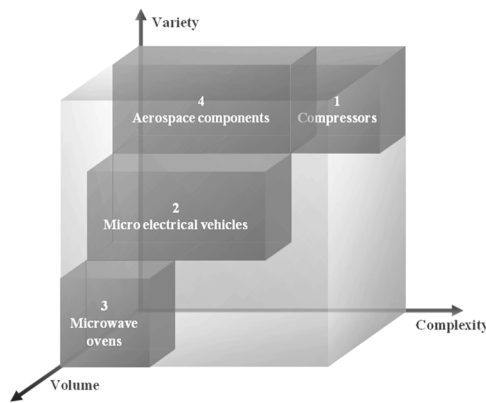

Figure 1: PERFoRM Use Cases

In Figure 1, the differences of the use cases, in terms of lot sizes volume, product variety and complexity are compared.

Compressors and aerospace components are characterized by high variety and small production volumes. Conversely, micro electrical vehicles are produced in medium lot sizes, while microwave ovens are produced in high quantity and present low variety of components.

Aerospace components can vary from low to medium complexity, as well as micro electrical vehicles. Microwave ovens are characterized by low complexity, while the complexity of assemblies of compressors is very high. The key challenge of the first use case is the production of small lot sizes of customized compressors for the oil and gas industry in an increasing rapidly changing manufacturing environment and high customer demands at the same time. The objective is to demonstrate the potential of using cyber-physical systems in terms of machine data acquisition and smart processing for predictive repair and maintenance for a better maintenance planning. The goal is to improve prediction strategies to increase productivity and reduce maintenance costs. The implementation of highly flexible production resources with increased availability of machine tools will result in significantly reduced delays, interlocks and therefore, fixed capital. This is necessary for increased product delivery reliability and ability to react to changes in customer demands. The high product safety levels and testing and traceability requirements will even be increased by retrofitting existing production to act as decentralized intelligent machines.

The second use case deals with the assembly of low cost full electric vehicles with high variants and high quality on low budget assembly lines. High flexibility is needed here to process all variants of electric vehicles, i.e. from a passenger vehicle to a delivery van, on the same workstations, taking into account quality-environment standards and safety protocols. By means of high degree of automation systems, it is expected to improve the efficiency and reproducibility of processes and enable highest product qualities, reducing re-work of sub-modules and part rejection and minimizing the variability of manual operation, namely human errors and manual actions.

The third use case focuses on the production of four types of built-in microwave ovens in already partly automated production system. The challenge of this use case is the lack of available real-time shop floor data and its integration into the production system controlling and planning. The intent is to establish a real-time KPIs monitoring system able to correlate the dynamic behavior of the factory with its static factors in order to forecast the general performance allowing its fast reconfiguration. By implementing automation solutions, a different approach will lead to a better and more accurate management, increasing productivity, traceability, efficiency, flexibility, reconfigurability and real-time control.

The fourth use case plans to build and demonstrate a flexible and reconfigurable production cells for different families of complex, high-value jet engine components with rigid quality characteristics. The components are designed and produced using advanced materials and processes to meet the specifications and requirements for their function, performance and reliability. The production system has to cope with a large variety of different components, low volumes, and varying demands. The use case's aim is to demonstrate more agile and automated production using a new integrated system that can complete a short sequence of common operations in the value adding process chain. The approach is to develop a modular production cell concept that can be reconfigured with different automated or semi-automated processes. The cell and process modules should be easy and quick to change over depending on current production demands in line with the ideas of plug-and-produce for Cyber Physical Systems.

The final goal here is to implement and validate the integrated solution developed within the PERFoRM project in

these four real industrial environments to verify valid improvements in production and to establish the condition for the future smart-flexible manufacturing system.

As lesson learned from the experience of former research projects, it can be said that developing a technical solution is not enough to guarantee its deployment in real manufacturing systems and machines but also validation and demonstration activities are necessary. Pre-industrial validation facilities will be used to demonstrate the technological readiness of the integrated solution, however, also a migration planning definition should be considered. Industries need support for performing the integration and deployment, in order to minimize risks and maximize the use and value of the demonstrations. Therefore, PERFoRM will implement methods and strategies for transforming existing production systems into plug and produce production systems.

IV. STATE OF THE ART METHODOLOGIES

Several approaches and methodologies on flexible and reconfigurable manufacturing systems have been developed for years by different researchers. Here a collection of former projects with main focus on this area is reported, distinguishing by the main used technologies.

a) Multi-Agent Systems and Plug & Produce technology

Multi-Agent Systems (MAS) are one of the most common approaches to realize the control architecture of such production systems [4]. Many projects used the agent technology to develop a decentralized control architecture. GRACE (inteGration of pRocess and quAlity Control using multi-agEnt technology) developed a multi-agent architecture that operates at all stages of a production line integrating process control with quality control [5]. The MAS architecture was applied on a washing machine production assembly line and tested against planned and unforeseen variation of variables. IDEAS (Instantly Deployable Evolvable Assembly Systems) developed a fully distributed and pluggable mechatronic environment, based on agent technology, capable to self-organize itself [6]. The assembly system operated with a totally distributed multi-agent control system.

Furthermore, "Plug and Produce" technologies were investigated to build modular structures that can integrate intelligent components. Following these principles, ReBORN (Innovative REuse of modular knowledge Based devices and technologies for Old, Renewed and New factories) aims at delivering models and methods for innovative factory layout design with modular plug-and-produce equipment and flexible low-cost mechanical systems [7]. I-RAMP³ (Intelligent Reconfigurable Machines for smart Plug & Produce Production) used plug-and-produce devices, sensors and actors with built-in intelligence for fast exchange of components with the intention of enabling the industry towards zero ramp-up time integration of additional capabilities in existing and new production networks [8]. CassaMobile (flexible mini-factory for local and customized production in a container) realized a new kind of flexible plug-and-produce production systems, for highly customized goods, easily reconfigurable being equipped with intelligent and self-adaptive process modules [9].

In some projects, MAS systems were used to enable plug-and-produce, as seen in IDEAS, and self-adaptation capabilities. PRIME (Plug and pRoduce Intelligent Multi-agent Environment based on standard technology) developed a multi-agent architecture using plug-and-produce principles for semi-automatically configuring production systems through innovative human-machine interaction mechanisms [10]. The multi-agent architecture here is used for module integration including legacy systems.

b) Service-oriented Architectures and Cloud technology

In parallel, other projects investigated on the use of Service-oriented Architectures (SoA) with Web services. SOCRADES (Service-Oriented cross-layer infrastructure for distributed smart embedded systems) developed a design, execution and management platform for distributed smart embedded systems, exploiting the SoA paradigm both at device and application level [11]. The use of a device-level service-oriented architecture contributes to the creation of an open, flexible and agile environment by extending the scope of the collaborative architecture approach through the application of a unique communication infrastructure. Starting from an evaluation of the SOCRADES results, IMC-AESOP (ArchitecturE for Service-Oriented Process-Monitoring and – Control) investigated a service-oriented architecture approach for monitoring and control of very large scale process control applications [12]. The project demonstrated that the SoA-based approach can simplify the integration of monitoring and control systems on application layer, and enables cross-layer service-oriented collaboration among cooperating devices and systems and also between systems located at different levels of the enterprise architecture. Self-Learning (reliable Self-Learning production systems based on context-aware service) developed high reliable and secure service-based self-learning production systems aiming at managing the world of secondary processes with the world of control by using context awareness and data mining techniques [13]. Within SoA the different processes are represented as services, which are fully interoperable and re-usable for specific process reoccurrences. FLEXA (advanced FLEXible Automation cell) used service-based concepts to develop a flexible cell controller for manufacturing a generic process chain to deliver quality assured parts for the aerospace industry, taking care of safe human interactions [14].

Moreover, Cloud technologies have been used in SelSus (health monitoring and life-long capability management for SELf-SUStaining manufacturing systems) to build a common data model integrated into the MES system, connecting and storing components data together, for systematic knowledge generation in the design phase and knowledge gathering and refining in the usage phase of an assembly station. Some projects demonstrated that SoA and Cloud technologies are complementary [15]. ManuCloud (Distributed Cloud product specification and supply chain manufacturing execution infrastructure) developed a service-oriented cloud manufacturing environment as a basis for the next level of manufacturing networks by enabling production-related inter-enterprise integration down to shop floor level [16].

c) Others

An integration of different solutions was developed by ARUM (Adaptive pRodUction Management) [17]. The project proposed a solution that combines holonic-MAS with SoA using Intelligent Enterprise Service Bus (iESB) to improve strategic medium-long term planning and control systems for

complex and small-lot products manufacturing, and to validate the solution in different environments. Innovative planning and control tools were the main focus also for EMC²-Factory (Eco Manufactured transportation means from Clean and Competitive Factory), that developed procedures for systematic identification of improvement measures for energy efficiency in factories and methods and tools for energetic improvement, integrating new and existing interdisciplinary solutions [18]. Finally, Self-adaptive procedures and optimization mechanisms were implemented by GRACE, CassaMobile and FRAME (Fast Ramp-up and Adaptive Manufacturing Environment) [19], which developed new control and human machine interaction strategies to enable future assembly systems to become self-aware, self-learning and ultimately self-adapting during ramp-up and proactively react to disruptive events.

d) Conclusion

Several solutions have been developed for a new generation of agile manufacturing using multi-agent systems, web services, standard communication protocols, or network of cyber-physical components, but they have never been completely applied into an industrial environment for many reasons. Different barriers should be overcome to assure industries an effective migration towards Cyber-Physical Production Systems:

1. *Integrated solution:* each project developed individual successful solutions in this topic, but never focusing on the overall production system. In order to facilitate a wider industrial uptake, it is necessary to integrate these technologies in a unique form, covering the architecture, assets, standard interfaces and process aspects involved in the industrialization of cyber-physical production concepts.

2. *Business and strategic goals:* the development of technologies and methodologies for flexible production systems is not enough to fit all the expected goals. A deep analysis of general business requirements and key performance indicators should be carried out in order to select and personalize the solution suitable for the specific use case.

3. *Human perspective:* specific attention needs to be paid also to the "human factor" in production as human operators will directly interact with the new robots and machinery. Education and training activities become important to improve human operators' technical skills, keeping them involved into the innovation process and motivated at the same time. The flexibility of the human worker is a highly valuable asset and it is necessary to enable the successful transition to CPPS factories.

4. *Technological maturity:* another obstacle for the industrialization of the cyber-physical production approach is the relatively immaturity of available technologies. The technological readiness of agile, plug-and-produce solutions has to be raised and fully tested in industry. The cost aspect of the digital technologies including the necessary sensing plays hereby an important role.

5. *Migration:* the implementation of new control technologies will have a direct impact on the production, thus, a real migration strategy that supports industry in adopting the next generation of agile production system step by step is necessary. Changeover methods need to be defined to integrate legacy systems in the new production concept and assure a smooth migration towards CPPS.

V. PERFoRM APPROACH

In order to achieve the real industrial exploitation of CPPS, the PERFoRM approach will work out the issues analyzed in the previous section. In this section the activities carried out so far within the project are presented. Firstly, the methodology used to collect advantages of agile, business and functional requirements and to define the related KPIs is described. Then, an illustration of the human and organizational perspective, as a complement to the technological viewpoint, is provided. Finally, the technology analysis approach to evaluate and identify the future-save technology and tools is defined.

A. Requirements analysis

According to the objectives of PERFoRM, a proper method is needed in order to show the ability of the next generation of agile manufacturing tools to guarantee the flexibility and the fast reaction of manufacturing environment to the rapid market changes. The first step to be taken is to understand how the implementation of such tools based on CPPS paradigm could occur not only within the shop floor but also at more strategic levels. Hence, an iterative approach for requirements identification is applied, essentially based on Requirements Engineering (RE) and on the methodology developed in MSEE project [20]. This methodology, as shown in Figure 2, includes four phases (i.e. Elicitation, Analysis, Specification and Validation) which are repeated in two different moments.
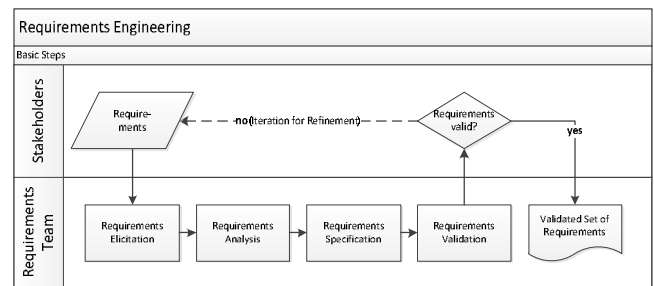

Figure 2: Basic Steps of Requirements Engineering [21]

The main task of the Elicitation phase is to verify, update and detail the end-user scenario. The Analysis aims at examining the current situation (AS-IS) and identifying weaknesses and opportunities for improvement (TO-BE situation). The Specification phase translates the identified gaps into an understandable form, taking into account their completeness, consistency and accuracy. The last phase (Validation), which is applied during the second iteration, has to validate the obtained requirements against the project objectives and the Industrial Partners' expectations.

Finally, to monitor and control the requirement trends a proper approach has been defined to identify the linkage existing among the company strategic objectives, the requirements previously obtained and a set of performance indicators (PIs) to measure them.

This approach, based on ECOGRAI methodology, considers the requirements as decision variables on which it is possible to act in order to reach the aforementioned objectives, ensuring coherence and consistency to overall structure. In this way, it has been possible to collect advantages of agile, business and functional requirements and to define the related KPIs. The relevance of these activities is related to the

maximization of the real impact of the implementation of the new technologies (CPPSs) and the simplification of their impact measurement according to the use cases.

B. Human perspective

The PERFoRM approach also addresses the integration of humans within CPPS, aiming at increasing the overall flexibility. The success of migrating production towards reconfigurable and adaptable systems, in fact, highly depends on the capability to properly rethink and support human activities. This objective is pursued through the development of use case scenarios referring to different phases of the manufacturing system lifecycle, which is fundamental to capture all the emerging challenges and opportunities for re-designing human tasks and interventions. The use case scenarios focus on two main levels of human activities: i) workers directly performing or controlling the production processes; ii) workers dealing with a mesh of cyber physical systems and applications. The analysis of the two levels within the use case scenarios leads to the identification of a set of needs and requirements targeting human integration and covering people competences, methods, organizational and interaction aspects.

The analysis emphasizes that, to be able to unleash the full potential of the novel production paradigms, employees need to acquire new knowledge and skills, along several dimensions, including robotics, ICT, quality, maintenance, etc. They need to gain a multi-perspective view and grip on manufacturing processes, to be more flexible and require routine training. By this, novel visualization and human-machine interaction strategies need to be developed that put the worker in the center so that in case of technological problems the worker can reactivate the systems. The involved employees need to acquire competences in modeling and simulating complex systems, in multi-objective and multi-stakeholder decision-making. In both cases, human activities require technological support to overcome physical, perceptual and cognitive limits and extend collaboration and sharing with colleagues, increase power, control, and responsibility over manufacturing systems. Furthermore, among all the possible research directions to improve the effectiveness of human activities, the PERFoRM approach addresses two particularly interesting topics: on the one hand, capturing experts' know-how in order to enhance systems capabilities to support complex phases of the production system lifecycle, such as the ramp-up; on the other hand, the development of intuitive and context-sensitive visualization of KPIs for enhancing strategic decision making.

C. Technological maturity

To create a flexible and agile production system, which incorporates the newly achievements of the state-of-the-art methodologies and fully meets the collected PERFoRM requirements, a prove-of-concept analysis of applicable technologies and tools [22] is required.

The following approach (Figure 3) describes six practical steps conducted during the project to verify the PERFoRM system and specify technology gaps. Steps *1a* and *1b* included a systematic research on existing solutions (i.e. previous European projects, overall research technologies, etc.) and the current situation (i.e. PERFoRM Use Cases) on the technological level.

To achieve this, three questionnaires were composed and presented to the PERFoRM consortium. Questionnaire I was used to examine the state of the art methodologies investigated within other European research projects in order to retrieve and systematize the overall background knowledge of the PERFoRM consortium. Questionnaire II was composed to analyze and evaluate each collected technology and tool from the expert perspective of its technology applier as experienced in previous projects. Questionnaire III was used to collect and evaluate missing technologies and tools based on the knowledge from the selected requirements of each Use Case. In addition to the required technologies, the respondents were asked to evaluate a set of currently used technologies and to provide additional information about utilized tools as well.
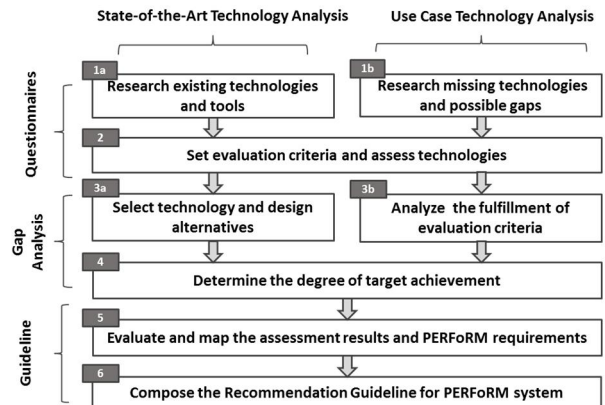

Figure 3: Technology Analysis and Guideline

To evaluate each technology a set of eleven assessment criteria was developed in *Step 2*. This set was designed to assess each technology regarding its full range of essential characteristics (criteria) and, thus, to generate a perspective strategy of how to prove a technology choice according to assigned scores. These assessment criteria are listed below:

1. *Usability*: degree of usability in manufacturing
2. *Maturity*: development status and readiness degree
3. *Automation*: level of automation
4. *Integrity*: level of integrity within other systems
5. *Benefit*: economic profit
6. *Substitution*: ability to be substituted by another competing technology
7. *Availability*: availability and support on the market
8. *Potential*: potential for the future market
9. *Robustness*: robustness and susceptibility degree
10. *Security*: availability of security mechanisms
11. *Industry 4.0*: relevance to Industry 4.0

During *Steps 3a* and *3b* the Gap Analysis regarding the future PERFoRM system could be started. This analysis included an overall review of 200 selected technology alternatives assessed in Questionnaires II and III. *Step 4* summarized the results of the Gap Analysis. For this purpose a degree of target achievements and a list of possible gaps could be specified for each Use Case. Subsequently, a detailed comparison of alternatives gained through the gap analysis and a visualisation of the mapped results could be done in *Step 5*.

Finally, in *Step 6* a comprehensive recommendation guideline with specification of technical interfaces and supported standards was developed and provided to the

PERFoRM partners. Figure 4 shows an outcome of the PERFoRM prove-of-concept analysis. The key findings specify the technology analysis gaps and technology matchings, which were found during the Step 5. The matching degree points out the ability to cover the technology gap referring to existing solutions developed in other European projects.

Technology Gaps	Matching Degree	Matchings
Distributed Processes and Process Control		
Digital Simulation Technologies		
System Architecture and Integration Middleware		IMC-AESOP
Communication Protocols and Interfaces		FLEXA
Robot Control and Production Cell		Research
Manufacturing Prediction System and Maintenance		Technologies SOCRADES
Scheduling System		ARUM
Integration Manufacturing Platform and CPS Integration		CassaMobile GRACE
Robot Operating Systems		SelSus
Plant Control, Logistics and Tracking		I-RAMP³
PLM, Simulation and Production Automation		EMC²
Robots (Cobots)		ManuCloud PRIME
Production Monitoring, Error and Failure Control Systems		GKN Use Case Self-LearningR
CPS and Integration Flow Control		ReBorn
Track and Tracing		

Figure 4: Key findings of prove-of-concept analysis. Matching degrees: from high (dark gray) to none (white).

Taking into consideration the degrees of matching results and the fact that PERFoRM consortium is able to provide the technological solutions, which can cover all technology gaps, the PERFoRM concept can be considered as proved. This means that the PERFoRM consortium has all resources to create a flexible and agile production system as specified in this approach.

VI. SUMMARY AND OUTLOOK

The PERFoRM project aims to achieve an integrated solution for next generation agile CPPS. The initial activities conducted in the project to realize these objectives have been presented. Firstly, a collection of the state-of-the-art methodologies and technologies developed by former projects is provided and the best available technologies are analyzed, as well as the technology gaps that need to be considered in the development of the PERFoRM solution. In parallel, the requirements of the use cases are identified, throughout an iterative approach, taking into account also the human perspective and analyzing how the human role will change in the future CPPS. Future work is related to the integration, harmonization and standardization of the selected technologies in a unique solution, which will be tested and demonstrated in real industrial environments. The implementation of the new solution will be supported by a migration strategy to ensure the real exploitation of the project results.

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