

Instantiating the PERFoRM System Architecture for Industrial Case Studies

Paulo Leitão, José Barbosa, Matthias Foehr, Ambra Calà, Pietro Perlo, Gregorio Iuzzolino, Pierluigi Petrali, Johan Vallhagen and Armando W. Colombo

Abstract The PERFoRM project, an innovation action promoted within the scope of the EU Horizon 2020 program, advocates the use of an Industrie 4.0 compliant system architecture for the seamless reconfiguration of robots and machinery. The system architecture re-uses the innovative results from previous successful R&D projects on distributed control systems domain, such as SOCRADES, IMC-AESOP,

P. Leitão · J. Barbosa (✉)
Polytechnic Institute of Bragança, Campus Sta Apolónia, 5300-253 Bragança, Portugal
e-mail: jbarbosa@ipb.pt

P. Leitão
e-mail: pleitao@ipb.pt

P. Leitão
LIACC – Artificial Intelligence and Computer Science Laboratory,
Rua Campo Alegre 1021, 4169-007 Porto, Portugal

M. Foehr · A. Calà
Siemens AG, Corporate Technology, Erlangen, Germany
e-mail: matthias.foehr@siemens.com

A. Calà
e-mail: ambra.cala.ext@siemens.com

P. Perlo · G. Iuzzolino
IFEVs – Interactive Fully Electrical Vehicles SRL, 12048 Sommariva del Bosco CN, Italy
e-mail: pietro.perlo@ifevs.com

G. Iuzzolino
e-mail: gregorio.iuzzolino@ifevs.com

P. Petrali
Whirlpool Europe, Cassinetta di Biandronno, Italy
e-mail: Pierluigi_Petrali@whirlpool.com

J. Vallhagen
GKN Aerospace Sweden AB, 46181 Trollhaettan, Sweden
e-mail: johan.vallhagen@gknaerospace.com

A.W. Colombo
University of Applied Sciences Emden/Leer, Emden, Germany
e-mail: awcolombo@technik-emden.de

GRACE and IDEAS. This paper, after describing the main pillars of the PERFoRM system architecture, focuses on mapping the system architecture into four industrial use cases aiming to validate the system architecture design before its deployment in the real environments.

Keywords Cyber-physical systems · Seamless re-configuration · Pluggability

1 Introduction

The Industrie 4.0 platform [7] provides a vision to modernize the manufacturing sector towards the smart factories of the future addressing the current requirements of product customization, quality and cost, as well as the rapid and flexible reaction of manufacturing processes to condition changes in terms of product variability and fluctuation and process disturbances.

Aligned with this vision, several distributed control architectures have been developed and proposed in the last years, some of them with European funding. From the literature survey, it is possible to name SOCRADES (Service-oriented cross-layer infrastructure for distributed smart embedded systems) [5], IMC-AESOP (Architecture for Service-Oriented Process—Monitoring and Control) [4], GRACE (Integration of pRocess and quAlity Control using multi-agEnt technology) [8], PRIME (Plug and produce intelligent multi-agent environment based on standard technology) [12], IDEAS (Instantly Deployable Evolvable Assembly Systems) [11] and ReBORN (Innovative Reuse of modular knowledge Based devices and technologies for Old, Renewed and New factories) [6] (a deep analysis of the results of these R&D projects can be found in [9]), that created the foundations and made the necessary proof-of-concept of these technologies and methods to face the described requirements.

Also aligned with the described challenges, the PERFoRM project was recently launched with the objective of the conceptual transformation of existing production systems towards plug&produce production systems aiming to achieve a flexible manufacturing environment based on the rapid and seamless reconfiguration of machinery and robots as response to operational or business events. PERFoRM will re-use the innovative results of these previous successful R&D projects and establishes an industry-oriented system architecture. The results of the PERFoRM project will be validated into four industrial use cases, which present different reconfigurability requirements and operational scenarios. This paper aims to map the general PERFoRM architecture to each one of these industrial use cases to validate the system architecture design before moving for its deployment in real environments.

The rest of the paper is organized as follows: Sect. 2 overviews the basics of the PERFoRM system architecture. Sections 3–6 describe the mapping of the generic system architecture into four industrial use cases, namely a large compressor producer, a micro-electrical vehicles producer, a home appliances producer and an aerospace components producer. Section 7 presents the compliance with Industrie 4.0, and finally, Sect. 8 rounds up the paper with the conclusions and points out the future work.

2 Generalized PERFoRM Architecture

PERFoRM introduces an innovative approach to handle the seamless production system reconfiguration, combining the plug-and-produce concept and the human role as a flexibility driver in future production systems. The architecture should be as open and generic as possible, allowing to cover as many production domains as possible, and should re-use the best results from the previous successful state-of-the-art R&D projects in the field, instead of developing a new architecture from scratch, which increases the possibility of its industrial adoption. From the existing architectures, PERFoRM derives and sets foundations from the IMC-AESOP [4] and in SOCRADES [5] projects, particularly the use of the Service Oriented Architecture (SOA) approach. In the GRACE project [8] is used for the integration of local and global perspectives and for the integration of quality control in the production process using a multi-agent system infra-structure and the ARUM (Adaptive Production Management) [10] with its integrated agent-based planning and scheduling systems for complex, small-lot products manufacturing, such as aircrafts and ships, which re interconnected using an Enterprise Service Bus (ESB). The ReBORN project [6] is also used as ground-base, particularly due to the developed software tools to retrieve and process maintenance relevant equipment status information. Additionally, the IDEAS [11] and PRIME [12] projects provided useful results related to evolvability and plug-and-produce perspectives.

As result, the system architecture is based on a network of hardware devices and software applications, addressing different levels of the ISA95 standard enterprise architecture, which exposes their functionalities as services following the SOA principles, and are interconnected in a transparent manner by using an industrial middleware, as illustrated in Fig. 1 [9].

The middleware is acting as a common interface between the diverse hardware devices (e.g., robotic cells and Programmable Logic Controllers (PLCs)) and software applications (e.g., MES and SCADA) presented at the PERFoRM ecosystem, ensuring a distributed, transparent, secure and reliable data flow between them. This interconnectivity allows achieving major technological objectives such as modularity, flexibility, pluggability and re-configurability on the shop floor, as well as business goals, such as the improvement of system's performance and efficiency. Additionally, an important innovation of this integration layer is its distributed and cloud approach, instead of the centralized ones that can be mostly found nowadays and can act as a single point of failure as well as a limitation for the system scalability.

An important architectural element to support the interconnectivity of heterogeneous hardware devices and software applications, and consequently supporting the integration of legacy systems, is the use of standard interfaces and technology adapters, enhancing the seamless interoperability and pluggability. In particular, these adapters are responsible to mask the legacy systems by exposing their functionalities according to the PERFoRM standard interfaces.

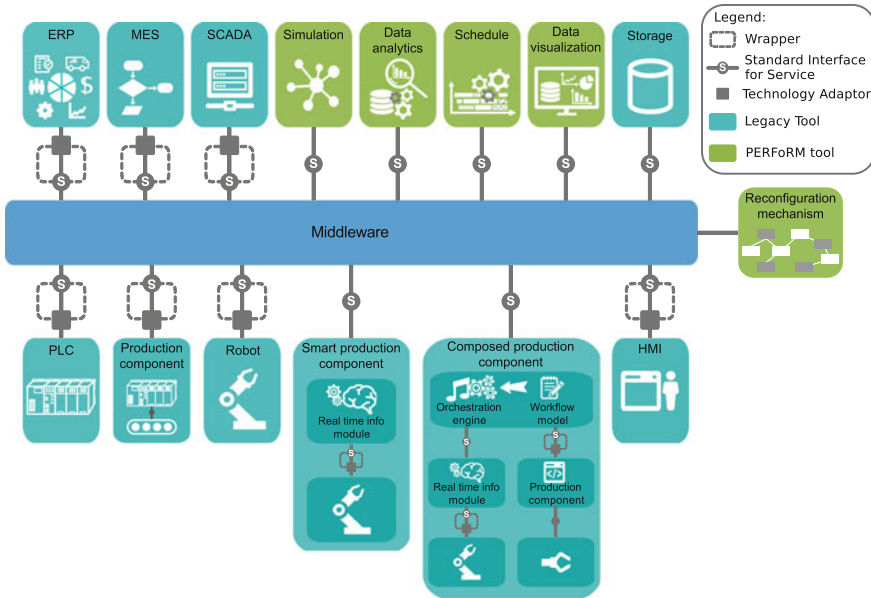


Fig. 1 PERFoRM system architecture

The human role, as in any system, is crucial by promoting a sustained decision making process. PERFoRM architecture has several interaction points with the human stakeholders, providing a bi-directional communication at different decision levels. Data analytics, scheduling and data visualization tools will have human dedicated graphical user interfaces to allow the insertion and display of relevant information. At a lower level, the PERFoRM architecture also allows the interaction with the human by means of Human Machine Interfaces (HMI) platforms, e.g. using the machine dedicated interfaces by empowering the human with mobile devices.

The proposed system also integrates advanced tools to enable the system operability, namely scheduling, simulation and intelligent decision support, some of them using Multi-agent systems (MAS) technology. MAS [13] is a suitable approach to provide flexibility, robustness and responsiveness by decentralizing the control over distributed, autonomous and cooperative intelligent control nodes. Despite these important benefits, the real time constraints and the emergent behaviour in industrial environments can be pointed out as weaknesses. However, the MAS tools developed in PERFoRM don't face soft or hard real-time restrictions since these tools are placed at strategic and/or tactical planning and control levels without real time restrictions. Additionally, the emergent behaviour should be seen as a potential benefit and not as a problem, since boundaries can be used to ensure stability during the emergency process. In fact, several commercial planning and scheduling solutions are already operating in big companies (see for example the MAS solutions developed by Smart Solutions [1], as well as the Gartner's Strategic Technology Trends

for 2016 report that predicts the use of MAS technology as a base for numerous mobile applications by 2020 [2]).

The PERFoRM architecture will be fully developed and instantiated into four industrial use cases, presenting different and specific requirements and covering a wide spectrum of production domains, namely a highly specialized large compressor production facility, a highly customizable producer of small-size electric vehicles, passing by a producer of home appliances and a producer of components to the aerospace industry. The mapping of the generic architecture into these use cases is described in the following sections, aiming to structurally validate the designed system architecture and also identify missing links and misunderstandings during the design phase.

3 Architectural Mapping for a Large Compressor Producer

3.1 Use Case Description

The first use case is related to a factory producing industrial compressors and gas separators. It is characterized by highly complex systems of several tens of thousand components which are typically only produced ones on a customer specific basis. At the same time, single parts can be very heavy and big, requiring special machining stations. As these stations are typically quite expensive, they cannot be set up multiple times within a factory. Together with machining times of several days up to 2 weeks, this produces critical delays and costs in case of machine failures and breakdowns. Currently, maintenance activities are done only reactively and in separated IT systems, namely the: a) maintenance scheduling and b) failure reporting. Thus, maintenance tasks are sometimes recognized too late and cannot be scheduled accordingly.

The objective of this use case process is to integrate the separate systems supporting the early identification of disturbances in production and the delivering to all involved stakeholders (e.g. maintenance, operation, scheduling and logistics) as much information as possible. Basically, three different scenarios can be distinguished when detecting early the disturbances: i) the machine can still operate (maybe with limited capabilities) and a future maintenance should be planned, ii) the machine cannot operate and a repair can be done right away, and iii) the machine cannot operate and maintenance will need to be carried out as soon as all needed material and resources are available. In the first two cases, the work does not need to be rescheduled. This integration, as well as the introduction of a proactive maintenance system, ensures a faster elimination of disturbances, and a reduction of delays in production and machine downtimes.

3.2 Architectural Mapping

Considering the particularities of the described use case, the general system architecture is mapped as illustrated in Fig. 2, where the generic blocks have been replaced by the legacy hardware devices and software applications installed at the plant or to be developed throughout the project. The maintenance tools and machines are the source of failure reporting and machine condition monitoring being their information stored in the Order Equipment Efficiency (OEE) database for further elaboration. Additionally, human operators can open up maintenance tickets, informing the maintenance staff about disturbances on the shop floor within the maintenance database.

Since they are legacy systems, proper technological adapters are required to transform their proprietary interfaces in the standard interfaces defined by PERFoRM. In addition, several new tools are considered to provide advanced features related to the analysis of the data gathered from the existing systems and now integrated. In particular, the data analysis tool aims at analyzing the collected data and at identifying in advance possible disturbances, generating warnings for the maintenance task list. The simulation tool aims at creating several *What-If?* scenarios which can be compared by KPI's, allowing the selection of the best maintenance schedule.

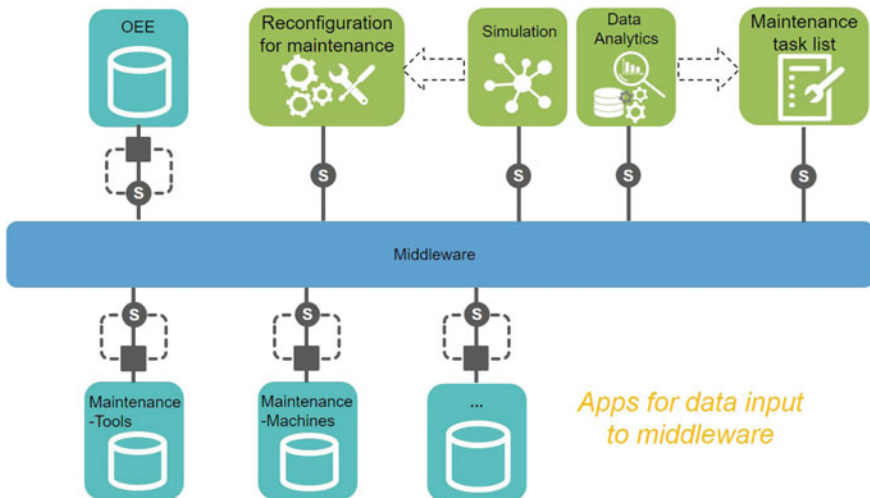


Fig. 2 Architecture mapping for the Siemens use case

4 Architectural Mapping for a Micro-Electrical Vehicles Producer

4.1 Use Case Description

The second use case considers a factory plant dedicated to produce micro-electrical vehicles. At the moment, the production line is actually operated completely manually with a welding operator in each island with also multi- skilled competences. The line is being automatized to support the production's efficiency and to permit the necessary flexibility for the production of different type of vehicle configurations (i.e. the easy switch from one vehicle configuration to another one).

This use case aims to enable a high quality production line for micro-electric vehicles, despite the throughput. For this purpose, the seamless integration of modular stations (each one composed by welding robots and Programmable Logic Controllers (PLCs)) is crucial to achieve flexibility and reconfiguration in the production system in order to allow the production of low amounts of micro-cars in an economical manner.

4.2 Architectural Mapping

Considering the particularities of the described use case, the general system architecture is mapped as illustrated in Fig. 3, where generic blocks were updated by the legacy hardware devices and software applications covered by the use case.

Several welding robotic cells, as well as the powertrain testing station (rolling bench test to check the functionalities of the motorized axle frame) and the chassis testing station (geometrical test of the chassis to check if all the assembly complies with the design), are interconnected to the MES system through the industrial middleware. In addition, agent-based simulation and dynamic scheduling tools are considered to increase the system performance and flexibility. These hardware devices and particularly the software application can access the data stored in the database also by using the middleware. The integration of these hardware equipment and software applications will require the use of proper technological adapters to transform the native data format into the data model defined by PERFoRM.

HMIs are related to the KPIs monitoring and visualization, and also used as graphical interface between the operator and the system for the production's traceability.

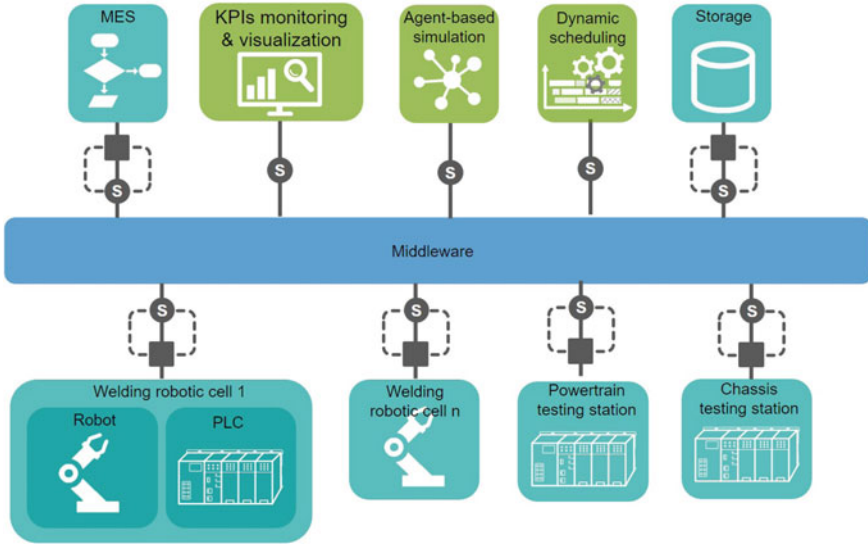


Fig. 3 Architecture mapping for the IFEVs use case

5 Architectural Mapping for a Microwave Ovens Producer

5.1 Use Case Description

The third use case is related to a factory plant dedicated to produce microwave ovens. The current factory continuous adaptation and medium term reconfiguration mechanism is based on a set of processes (Factory Master Plan, Profit Plan, Cost Deployment) which aim at improving KPIs through modification of factory assets and organization described by key business factors. Of course KPI are mainly driven by shop floor data of each single facilities and departments. The behaviour of these facilities is monitored in order to meet middle- and long-term goals to benefit. Currently, the data gathered at shop-floor level lack uniformity (different formats and source of data) and, moreover, correlation (i.e. each data is treated and analyzed without a model or a tool able to describe how each KPI is linked with others KPI or input factors or KBF).

The use case aims at developing a KPI visualization system to help the reconfiguration activities described above and ensuring a more data driven decision process. For this purpose, the data collected from the shop floor should be analyzed and correlated to extract in advance the KPIs and also to detect earlier possible disturbances or performance degradation. This analysis has to be complemented with simulation enabling a prediction mechanism to allow virtual reconfiguration before the actual one.

5.2 Architectural Mapping

Considering the particularities of the described use case, the general system architecture is mapped as illustrated in Fig. 4, where generic blocks were updated by the legacy hardware devices and software applications covered by the use case.

As shown, the data acquired from the shop floor and currently collected by several databases will be integrated in the PERFoRM ecosystem by the middleware and in a PERFoRM database. The integration of these legacy databases will require the use of proper technological adapters to transform the native data format into the data model defined by PERFoRM. Several new tools are considered to provide the required advanced features, namely: the monitoring and visualization system to support the on-line visualization of KPIs, the KPIs optimization tool that uses two different models (MPFQ-K model and Value Stream Map) to identify strategies to improve KPIs and a simulation tool having what-if game functionality to support the analysis of the impact of several degrees of freedom in these KPIs.

The human-machine interaction is mainly reserved for key decision-makers (e.g., production and industrial engineering managers) that will use the monitoring and visualization tool, as well as the proper designed user interfaces for the simulation tool, to understand the current system performance and study how KPIs can be optimized.

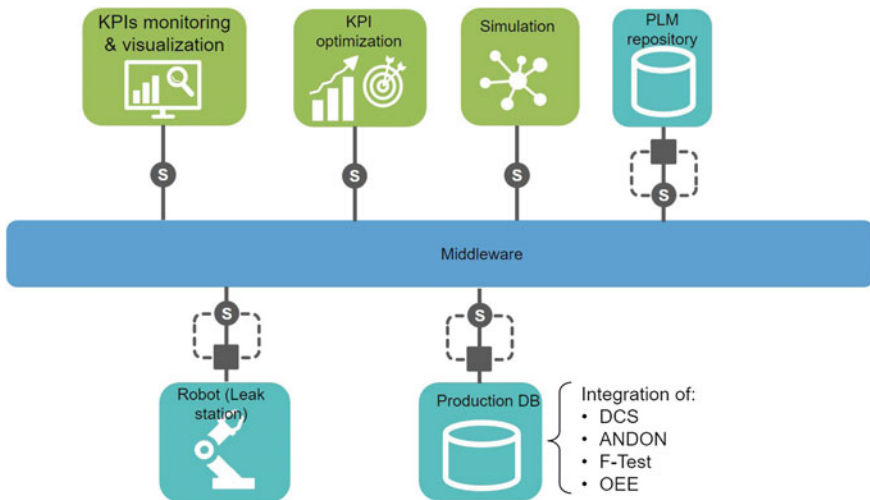


Fig. 4 Architecture mapping for the whirlpool use case

6 Architectural Mapping for an Aerospace Components Producer

6.1 Use Case Description

The fourth use case considers a factory plant that manufactures complex, high value jet engine components with very stringent quality characteristics. The production system extends a functional workshop with standalone work centres and a mix of dedicated and common resources. The level of automation is usually rather low and based on separate process automation cells with low level of process flow integration. The production system has to cope with a large variety of different components, low volumes and varying demands. All data (master data) is stored and managed through the SAP ERP system, which provides the functions for production planning, scheduling and MRP and collects different kind of documentation from the processing and inspection in order to guarantee traceability. Some additional data and information is generated and made available in the PLM system (Team Center Engineering and Manufacturing). The information flow in the typical day-to-day process is a straight communication between different IT systems of CNC-machines, robots and other equipment whereas the near term production planning and scheduling is done by shop floor planners based on ERP data for long term order scheduling and customer demands.

The main objective is the improvement of the flexibility to demonstrate more agile and automated production using an integrated system that can complete a short sequence of common operations in the value adding process chain. The approach aims 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 easily and quickly changed depending on current production demands aligned with the ideas of plug-and-produce for cyber-physical systems. The business oriented criteria are to reduce lead times and increase the level of automation as well as equipment utilization. For this purpose, mechanisms for the seamless reconfiguration of the production process should be addressed by plugging-in/-out modular processes in robotic stations.

Several technical challenges need to be addressed, namely interfaces for process modules that allow simple and short change over time, methods for production cell planning and scheduling to maximize throughput, and decision support to identify when to reconfigure the cell to have the best impact on cost and production lead time.

6.2 Architectural Mapping

Considering the particularities of the described use case, the general system architecture is mapped as illustrated in Fig. 5.

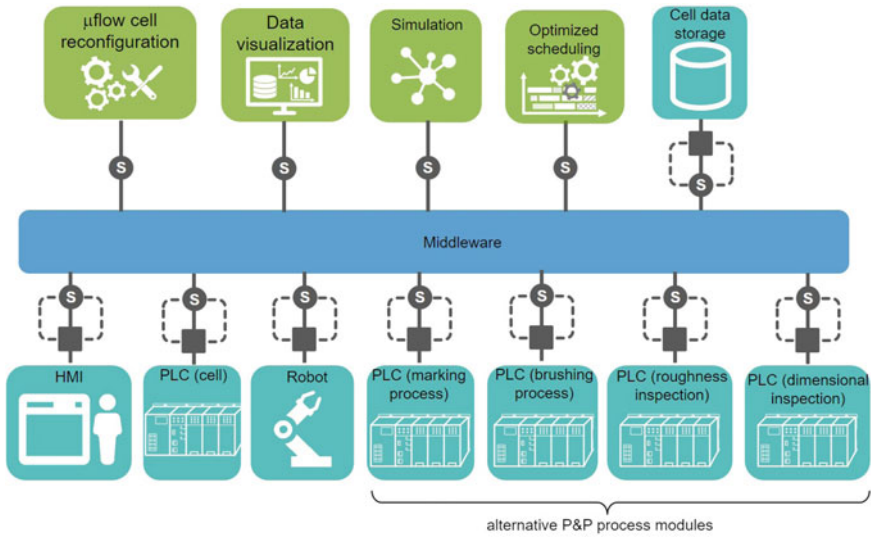


Fig. 5 Architecture mapping for the GKN use case

The modular micro-flow-cell? concept has a base configuration and components to host, control and coordinate the production on the process modules. The cell functions are a PC, PLC for communication and control, a robot system for part handling and processing and the safety system for the cell. Each of the different process modules, that can be replaced with short lead time “plug and produce” have their own PLC running the local control system.

All process related code/process parameters are downloaded from a central database, through the industrial middleware, to guarantee the full control of the configuration and versions of programs. In a similar way, the data generated from the executed processes and/or inspections are uploaded to the ERP system or databases and related systems for analysis and visualization (e.g., OEE/Stop time analysis and statistical process control). The production planning and scheduling is planned to be supported by the optimized scheduling and simulation tools that will ensure the short-term and long-term scheduling, well will trigger the need for use of the cell flexibility and reconfigurability, i.e. when to make the change-over in the cell.

The human interaction will be performed in two manners: i) at strategic level, a data visualization tool will provide to the cell manager a plethora of information related to the current status of the cell, namely current operating processes and tools, as well as KPIs, and ii) at production cell level, a HMI supports the operator during its tasks.

7 Alignment with Industrie 4.0 Platform

The concepts currently being developed within the PERFoRM project are aligned with the current state-of-the-art and road-map trends. Several matches can be devised from “regulatory” documentation [3, 7, 14].

From [7] several scattered key concepts can be seen. CPS are at the cornerstone of the Industrie 4.0, and PERFoRM addresses this by setting its foundation in the CPS concepts, particularly by promoting the symbiotic use of “digital” and “physical” layers of the manufacturing world and also considering its interconnection and interoperability. Optimized decision-making is also refereed in [7] and PERFoRM is addressing this by promoting a set of different tools that will allow the decision-makers, and particularly each of the use cases, to early detect deviations and performance degradation, allowing to take better, more accurate and timely decisions. Integration, either vertical and/or horizontal, is also mentioned to be crucial. PERFoRM also addresses this by promoting the use of a common PERFoRM data model, covering data needs from lower levels into higher levels as also from different domains within the same level (e.g., considering different data needs of devices) and by considering a distributed and interoperable middleware. Finally, and considering only a few key concepts, the “Industrie 4.0 working group” also recommends the development of a reference architecture. This is currently being developed by the Industrie 4.0 Platform, named “Reference Architectural Model Industrie 4.0 (RAMI 4.0)” [14], but from the initial developments, PERFoRM is aligned with what is being considered in RAMI 4.0.

Aligned with what was aforementioned, the International Electrotechnical Commission white paper on Factories of the future also makes several remarks and recommendations [3]. The “connectivity and interoperability” is covered through the development of a distributed and interoperable middleware alongside with the design of a common and cross-layers data model. The “*seamless factory of the future system integration*” is accomplished by the connection of several information data sources as also the consideration of the human as a valuable data source itself. The “*integration of existent systems*” is also managed by the development of hardware and software adapters, adapting the native information language into the PERFoRM ecosystem. Modelling and simulation is also envisioned as crucial building blocks of future systems. Therefore, the PERFoRM architecture considers the use of such tool domains, particularly allowing beforehand to foresee future problems and solutions to these and to allow the optimization of production processes. Other key concepts are located around the human operator and to its role in future production systems. PERFoRM considers this by moving the human to the centre of the architecture and by considering him as a flexibility driver in future systems. Therefore, a special emphasis is being devoted to the study of its integration and interaction to/from the system.

One of the most critical aspects being pointed out by all the reference documents is the use of standards and the promotion of the standardization process. The PERFoRM consortium also considers this as a major road-blocker breaker and enabler

for the architecture future adoption and is also promoting this topic by promoting the use of standardized approaches and technologies, e.g., using OPC-UA or AutomationML data models.

Finally, and as also stated in [7], “*The journey towards Industrie 4.0 will be an evolutionary process.*”, and also re-inforced in [3], the migration process from legacy systems is also crucial, particularly in the future adoption of such innovative systems. Therefore, the PERFoRM architecture is also complemented and accompanied with a set of migration guidelines that allow the successful deployment into both legacy and new production systems.

8 Conclusions and Future Work

This paper briefly introduces the generic modular system architecture developed under the H2020 R&D PERFoRM project, covering all the different layers in the production process identified by the ISA-95 automation model, being able to respond in a promptly manner to nowadays requirements as aligned with state-of-the-art visions, such as those advocated by the industry 4.0 initiative. The proposed system architecture doesn't set aside legacy equipment and tools allowing the majority of nowadays factories to migrate. This process is accomplished by the use of a common, cross-platform, data model and through the use of technological adapters.

In particular, the paper describes in general terms the instantiation of the generic system architecture into four project's industrial use cases, which allowed to test and validate the PERFoRM system architecture in its full spectrum of applications, ranging from different time constraints (from machinery to backbone levels) and also covering the horizontal (between machine to machine and software application to software application) and vertical integration (from automation hardware machines to planning and simulation software applications).

Future work will be devoted to the implementation, testing and validation of the instantiated use case architectures. Additionally, and in order to promote an effective architectural deployment, future work will be devoted to the study of migration strategies, converting the current existing production systems into PERFoRM compliant solutions. Particularly, the industry best practices in migration strategies within the several domains of ISA-95 are considered and aggregated.

Acknowledgements



This project has received funding from the European Unions Horizon 2020 research and innovation programme under grant agreement No 680435.

References

1. Smart Solutions. <http://smartsolutions-123.ru/en/>
2. Gartner Identifies the Top 10 Strategic Technology Trends for 2016 (October 2015). <http://www.gartner.com/newsroom/id/3143521/>
3. White Paper: Factory of the future. International Electrotechnical Commission. www.iec.ch (2015)
4. Colombo, A.W., Bangemann, T., Karnouskos, S., Delsing, J., Stluka, P., Harrison, R., Jammes, F., Martínez Lastra, J.L. (eds.): *Industrial Cloud-based Cyber-Physical Systems: The IMC-AESOP Approach*. Springer (2014)
5. Colombo, A., Karnouskos, S.: Towards the Factory of the Future: a Service-oriented Cross-layer Infrastructure. *ICT Shaping the World: a Scientific View*, European Telecommunications Standards Institute (ETSI), pp. 65–81 (2009)
6. Ferreira, P., Doltsinis, S., Lohse, N.: Symbiotic Assembly Systems—A New Paradigm. *Procedia CIRP*, pp. 26–31 (2014)
7. H. Kagermann and W. Wahlster and J. Helbig: Securing the future of German manufacturing industry: Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Technical report, ACATECH—German National Academy of Science and Engineering (2013)
8. Leitão, P., Rodrigues, N., Turrin, C., Pagani, A.: Multi-agent system integrating process and quality control in a factory producing laundry washing machines. In: *IEEE Transactions on Industrial Informatics*, pp. 879–886 (2015)
9. Leito, P., Barbosa, J., Pereira, A., Barata, J., Colombo, A.W.: Specification of the PERFoRM architecture for the seamless production system reconfiguration. In: *Proceedings of the 42nd Annual Conference of the IEEE Industrial Electronics Society (IECON'16)* (2016)
10. Marn, C.A., Mnch, L., Leito, P., Vrba, P., Kazanskaia, D., Chepegin, V., Liu, L., Mehandjiev, N.: A conceptual architecture based on intelligent services for manufacturing support systems. In: *Proceedings of the 2013 IEEE International Conference on Systems, Man, and Cybernetics, SMC*, pp. 4749–4754 (2013)
11. Onori, M., Lohse, N., Barata, J., Hanisch, C.: The IDEAS project: plug & produce at shop-floor level. *Assem. Autom.* 124–134 (2013)
12. Rocha, A., Orio, G.D., Barata, J., Antzoulatos, N., Castro, E., Scrimieri, D., Ratchev, S., Ribeiro, L.: An agent based framework to support plug and produce. In: *Proceedings of the 12th IEEE International Conference on Industrial Informatics (INDIN'14)*, pp. 504–510 (2014)
13. Wooldridge, M.: *Introduction to Multi-Agent Systems*. Wiley (2002)
14. ZVEI: *Industrie 4.0: The Reference Architectural Model Industrie 4.0 (RAMI 4.0)*. <http://www.zvei.org/Downloads/Automation/ZVEI-Industrie-40-RAMI-40-English.pdf>