Architectural Blueprint Solution for Migrating Towards FAR-EDGE

Ambra Calà
Siemens AG, Corporate Technology,
Günther-Scharowsky-Str. 1, 91058, Erlangen, Germany
e-mail: ambra.cala@siemens.com

Filippo Boschi, Paola Fantini, Giacomo Tavola, Marco Taisch
Politecnico di Milano
Via R. Lambruschini 4/b, 20156, Milano, Italy
email: {filippo.boschi, paola.fantini,giacomo.tavola, marco.taisch}@polimi.it

Abstract— **Over the last years, several technologies and control systems have been developed for enabling the decentralization of automation control architectures for cyber-physical production systems. However, none of these technologies are in use yet. To overcome manufacturers' conservatism, migration strategies and decision-making approaches are required to support the adoption of the next generation of smart production systems. This paper presents a migration approach tailored to the migration of legacy automation systems towards the Industry 4.0 paradigm. Considering that the implementation of a new, or even just modified production control will have a direct impact on the existing production systems, the aim of the proposed approach is to evaluate opportunities of improvement and mitigate the risks of migration from technical, operational, human and business perspectives. The methodology follows an iterative and incremental approach starting from the definition of the current situation of the factory and identification of business goals to the evaluation of possible migration paths and the selection of the optimal one according to a cost-benefit analysis. The paper presents the methodology and one of the architectural blueprints derived during the EU-project FAR-EDGE to migrate towards a cloud- and edge-based automation control architecture.**

Keywords: Industry 4.0; Decentralized automation control; Migration strategy; cyber-physical production systems.

I. INTRODUCTION

The combination of Edge-Computing (EC) with Cyber-Physical Systems (CPS) and Internet of Things (IoT) standards will virtualize the conventional automation pyramid, enhancing flexibility and scalability in integrating modern IT technologies and, consequently, increasing the efficiency and the performance of production processes [1]. Edge-computing provides a distributed architecture option, which considers a new functional layer in the Industrial Automation pyramid that places data processing and control functions at the very edge of the network and facilitates distributed real-time control and scalable data processing.

However, today manufacturers are still reluctant to adopt decentralized manufacturing technologies. They typically aim at obtaining the return on the relevant investment sustained for their production facilities and envision only sporadic and limited changes. Nevertheless, in order to reap the opportunities offered by the new technologies, changes during the whole life cycle of the devices and services should be performed. To this end, industries need to be supported with migration strategies to implement new technologies and decentralize the automation pyramid. Within the context of complex automation systems, a complete change from the legacy production systems to the emerging I4.0 compliant ones in one step, following the Big Bang approach, will have a negative impact in terms of high upfront investments, development time, and risk of production losses. On the contrary, a smooth migration strategy, that applies future technologies in existing infrastructures with legacy systems through incremental migration steps, could lower risks and deliver immediate benefits [2]. The challenge is to identify the architectural blueprints of the migration considering not only the technology dimension but also the operational and human ones from a business process point of view.

Migration strategies are expected to play an essential role to the success of the envisioned infrastructure. Therefore, FAR-EDGE will study smooth migration path options from legacy centralized architectures to emerging FAR-EDGE based one.

The paper is structured as follows: after this brief introduction, Section II outlines the FAR-EDGE project's goals and Section III presents the methodology defined and adopted within the project, while Section IV briefly describes the migration strategy and how it supports the identification of the architectural blueprints and migration paths towards the FAR-EDGE architecture by using the migration matrix. Section V presents one migration solution blueprint and its implementation roadmap based on the FAR-EDGE industrial use cases. Section VI concludes the paper with a summary and outlook.

II. FAR-EDGE PROJECT

FAR-EDGE (Factory Automation Edge Computing Operating System Reference Implementation) intends to exploit the combination among EC, CPS and IoT Technologies for virtualizing conventional automation pyramid, and enhancing production system reconfigurability [3].

To this aim, FAR-EDGE project proposes a new Reference Architecture (RA) (Figure 1) composed by:

1. Four horizontal Layers: Field, Edge, Ledger and Cloud.
2. Three functional viewpoints: Automation, Analytics and Simulation

FAR-EDGE identifies in the Field tier, which corresponds to the Level 1 in the ISA-95 pyramid, particular device called Edge Node, equipped with on board computing capabilities,

The Edge Layer includes SCADA (Level 2) and MES (Level 3) functionalities by following the Automation Pyramid terminology. In FAR-EDGE, it consists of Edge Gateways that execute all those production processes having a local scope due to time and bandwidth constraints. Finally, the Cloud layer could also include MES functionality and provides interfaces (Cloud Services) to the ERP (Level 4) of the ISA-95 automation pyramid. Compared to the Edge Layer, it includes production and business processes that do not have strict time requirements and do not bound to the factory.

The connection to the shopfloor is performed by the Field Abstraction Component that has specific requirements from the shopfloor automations and equipment. Thus, in addition to the 3 vertical functional viewpoints (Automation, Analytics and Simulation enabled by RA), a Field dimension is required, as it is a FAR-EDGE enabler. Therefore, if in some use cases specific requirements are not met in the field, the FAR-EDGE platform is not applicable.

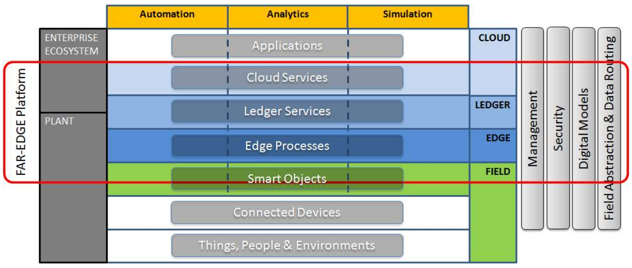

Figure 1. FAR-EDGE Platform

III. METHODOLOGY FOR MIGRATION

This section illustrates a methodological approach aiming at supporting decision makers in addressing the migration, i.e., transformation, towards FAR-EDGE. The approach encompasses the initial assessment of the current level of manufacturing digital maturity, the analysis of priorities based on the business strategy, and the development of a migration strategy. Specifically, an innovative holistic approach to develop a migration strategy towards the digital automation paradigm with the support of a set of best practices and tools is presented. The application of the approach is illustrated through the description of the blueprint solution in Section IV.

The overall approach is implemented according to the 5 steps described in Figure 2.

The identification of the factory analysis domains in Step 1 allowed a better understanding of the current situation of the production environment under technical, operational and human aspects. This task is supported by an assessment questionnaire according to the scope of the developed FAR-EDGE architecture. The second step of the FAR-EDGE Migration approach aims at the realization of the Migration Matrix and the selection of the appropriate digital maturity levels scale characterized for the three different dimensions of the factory, constituting a reference model that can be used to evaluate the AS-IS and TO-BE situations of a factory and analyse their gap. The Migration Matrix with the redefined digital maturity levels scale are described in [4].

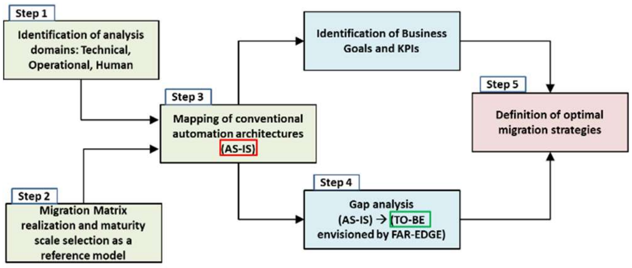

Figure 2. FAR-EDGE Migration Approach

The next step based on the mapping of the conventional automation architecture within the Migration Matrix, needed to analyse the possible different starting points of migration and to define accordingly a kind of library of reusable blueprints architectures towards FAR-EDGE.

The gap analysis between the TO-BE situation, namely the edge based distributed architecture envisioned by FAR-EDGE, and the AS-IS situation of the factory, considers the methodology described in [5] to point out the business goals and KPIs, in order to define the optimal migration strategy for the specific use cases.

Finally, the approach ends by providing a set of blueprint solution that can ensure a smooth and low risk digital transformation of traditional production systems to digital automation solutions, notably the automation, simulation and analytics solutions that are aligned to the FAR-EDGE reference architecture.

In this way, the approach provides a clear map of the current (AS-IS) and desired (TO-BE) conditions of a factory, revealing different alternatives to achieve a specific goal, by means of a digital automation system and towards the vision of digital factory.

Moreover, this approach enables the evaluation of the potential alternatives according to the business strategy, considering also strengths and weaknesses points. Based on this evaluation, the migration approach ends-up specifying adequate architectural blueprints that match the needs of the organization and the estimation of the overall benefit of the digital automation solution for the analysed production system.

IV. MIGRATION PROCESS

The first part of the migration approach previously mentioned is based on an assessment questionnaire. It has been developed in order to assess the current status of a factory at technical, operational and human dimensions. The assessment aims at evaluating the digital maturity level of a factory in comparison with the digitalization envisioned by FAR-EDGE. For this reason, the questionnaire is structured according to the main functional domains of the FAR-EDGE Reference Architecture: automation, analytics, and simulation. The “Automation” mainly concerns the capability to utilize instructions to create a repeated process that replaces an IT professional’s manual work in data centres and cloud deployments. In this context, the automation accomplishes a task repeatedly without human intervention. The “Analytics” involves those activities related to multivariate analysis of a process aiming at developing a statistically based understanding, leading to process improvement and/or optimization. The “Simulation” is closely related to the digital factory concept, which offers an integrated approach to enhance the product and production engineering processes and simulation is a key technology within this concept.

In order to create a more coherent questionnaire, the interrelationship between functional domain (Automation, Analytics and Simulation) with the three dimensions applied: (Technical, Operational and Human) has been needed.

The “Automation – Technical dimension” section aims at collecting information related to the current automation system in production, i.e. the structure of the automation architecture and the legacy software and hardware. Particular relevance is also given to the type of the connectivity among these systems, and the existing security and access control mechanisms. Related topics include the monitoring support in production for errors and performance [6].

The “Automation – Operational dimension” section is related to the so-called “Orchestration” concept. This is a broader concept wherein the user coordinates automated tasks into a cohesive process or workflow for IT and the business process. In this context, automation is seen as the capability to manage and to integrate different information in an automatic way [6].

The “Analytics – Technical dimension” section is related to the possibility to utilize data and information needed to carry out the analysis to provide the value added to management approach [6].

The “Analytics – Operational dimension” section takes into account the company inclination to manage a basic manufacturing process controlling the input factors (especially chosen by decision makers) and the fixed inputs (defined by the current context) and monitoring the uncontrollable or nuisance variables aiming at evaluating and optimizing the output responses [6].

The “Simulation – Technical dimension” section sees the simulation as a technology that provides design engineers with the right tools, the right hardware—at the right time—to make better decisions. It requires Integration of CAD designs and CAE information, connecting multiple simulation models, and data synchronization of the engineering processes requiring access to all necessary product and process information [6].

The “Simulation – Operational dimension” section concerns the enabled dynamic analysis and optimization of material flow, resource utilization and logistics for all levels of plant planning from global production networks, through local plants down to specific lines. In these terms, the relevant goal of simulation is to provide all users to quickly assess the impact of their decisions on product, process, plant and resource requirements [6].

The “Human dimension” section concerns the social readiness to cope with the functional domains and the related technical and operational facets, namely it is related to the level of awareness and know how that are characterizing the company organization. It takes into account also the capability of the human resources to extract the valuable data and to carry out a disciplined engineering and scientific methods to identify and control the factors that impact the business value of the company [6].

Based on the answers of this questionnaire, different migration scenarios according to the possible technology options are investigated in order to identify the migration alternatives to go from the identified AS-IS situation to the TO-BE one [1] . To this end, a tool called Migration Matrix has been developed within the FAR-EDGE project to identify all the necessary improvements in the direction of the Industry 4.0 vision of smart factory, splitting the digital transformation in different scale-levels. Thus, the matrix represents a multiple impact dimensions, aiming at providing a snapshot of current situation of companies and suggesting which steps should be achieved in order to reach the FAR-EDGE objective in a smooth and stepwise migration process.

The migration matrix is structured in rows and columns. The rows represent the relevant application fields selected during the preparation phase with high potential of improvement by FAR-EDGE concepts implementation on the architecture. Meanwhile the columns the development steps for each application field towards a higher level of production flexibility, intelligent manufacturing and business process in the direction of a digital automation implementation [1]. The development steps are divided in five columns representing five levels of production system’s digital maturity, based on the integrating principles of both the Capability Maturity Model Integration (CMMI) framework [7][8][9], and DREAMY model (Digital REadiness Assessment MaturitY) [10] .

V. MIGRATION SOLUTION BLUEPRINTS

A traditional manufacturer aims at decentralizing the current factory automation architecture and introduce cyber-physical system concepts in order to flexibly deploy new technologies and maximize the correlation across its technical abilities to support mass-customization. Target of the implementation of the FAR-EDGE platform is the reduction of time and effort required for deploying new applications by the automatic reconfiguration of physical equipment on different stations, according to the current operation, and its automatic synchronization among different information systems (PLM, ERP, and MES [11],[12]).

A factory that currently presents an automation architecture compliant to ISA-95 standards with three layers (ERP, MES, and SCADA with Field devices) could have potential issues during the integration of new applications at the MES level to obtain new functions at the shop-floor. In fact, it could be very expensive because of highly dependent on the centralized control structure of the architecture.

Moreover, it requires a long verification time and, consequently, a long delivery time to customers.

From this context, one of the project's goals was to provide a set of architectural blueprints based on the use cases that have been developed within the project. The main objective is to show the benefits of the FAR-EDGE architecture and few possible application scenarios with reference to one or more functional domains of the platform. This section presents one of these architectural blueprints, i.e. the migration towards production optimization by means of the simulation functional domain of the FAR-EDGE architecture.

A. Simulation functional domain

FAR-EDGE Simulation provides functionalities for simulating the behaviour of physical production processes for the purpose of optimization or of testing What-If scenarios at minimal cost and risk and without any impact of regular shop activities. Simulation requires digital model of plants and processes to be in-sync with the real-world objects they represent. As the real-world is subject to change, models should reflect those changes. For instance, the model of a machine assumes a given value of electric power / energy consumption, but the actual values will diverge as the real machine wears down. To detect this gap and correct the model accordingly, raw data from the Field (direct) or complex analysis algorithms (from Analytics) can be used.

To explain how a typical migration roadmap to the FAR-EDGE Simulation functionality can bring industrial benefits, the What-If scenario use case based is here described.

A traditional factory will benefit from the adoption of simulation and what-if analysis especially about the evaluation of the impacts of variations in the production conditions, including changes in the capacity, changes in the production plan, changes in the production mix, as well as the changes in physical configurations.

From a technical point of view a capacity to create a digital model to reproduce the actors and the activities carried out within the shop floor is required. Furthermore, decentralized architecture that enhances the automatic integration of data, information and results coming from the overall context of the company such as the market, the customer requirement or the internal processes, is needed. Finally, the real time and remote communication will need to be carried out for initiating and updating parameters exchange for example at the beginning of the production. This requires standard communication protocols.

Moreover, the role of employees can be affected by the new technological and operational changes. A typical design engineer should improve his/her skills and his/her know how on utilizing new technologies based on design and simulation activities and typically integrated with ICT aspects.

For example, the added implementation of communication tools in simulation process means that feedback loops are growing ever too common to the modern engineer. Feedback loops are great when it comes to affecting the design positively, but they often mean a nightmare to the untrained engineer. With the growing capability of cloud-based programs, engineer's work is now often monitored or analysed in real time. This opens up the door for collaboration and greater innovation, but it means that as engineers, we need to be able to communicate.

B. Deployment of FAR-EDGE Simulation – Roadmap Implementation

The virtual representation of the physical objects in cyber space can be used for optimization of the production processes. For example, the cyber modules have the ability to avoid getting stuck in local optimization extremes and are able to find the global maximum and minimum which results in high performance. Therefore, the integration of digital models should be considered as a first step.

In addition, the existing CAD systems will be interfaced to each other, and secondly, they will be fully integrated to enable the optimization of equipment reconfiguration through intelligent simulation tools. In the same way, the production will be optimized based on the integrated information derived from the CAD designs and then it will be automatically implemented through the intelligent tools. To this end, the production process models and their different layout versions will be first integrated with business functions, in order to align the process parameters with cost deployment and profitability measures.

From an organizational perspective, the main implications affect the roles of product designers and production engineers: they need to increase their level of cooperation to model all the relevant aspects of the manufacturing processes into the CAD. Furthermore, the production engineers have to see that the models of the CAD are connected to the models of the actual production facilities, so that the production can be simulated, planned and monitored. Therefore, the competences of the above-mentioned roles require to be enhanced with new skills concerning digitalization, modelling and simulation. Furthermore, the tasks and responsibilities of these roles have to be updated, accordingly.

The FAR-EDGE architectural blueprint for simulation and what-if analysis comprehends the following components:

- CPS Model Synchronization
  - Synchronization Services
  - Open API for Virtualization
- Edge Infrastructure
  - Data Routing & Pre-processing
  - Field Abstraction
- Ledger Infrastructure
  - Distributed Ledger

The Field Abstraction Component provides the mechanisms for configuring and controlling shop floor equipment and to receive asynchronous events and alarms from it. It is composed of informatics istance that, exploiting a bi-directional, low bandwidth communication, can exchange high frequent message. In this way, it is possible to obtain the abstraction of the low-level technical details of field components interactions.

The Data Routing & Pre-processing Component provides the mechanisms to move massive streams of data from the Field Tier to the upper Tiers of the Platform. In this case, the communication is unidirectional (upstream). Using this module, the acquisition and the pre-process of large amounts of data from heterogeneous sources can be pointed out, merging them into a common schema.

From the implementation of these two components of the edge infrastructure, it is possible to instantiate a digital model of the shop floor and to populate it with set of heterogeneous data. The digital model facilitates an intermediate step where the integration of CAD systems with other design tools can be obtained. In this way, it is possible to leave the approach in which each simulation system was fed by manually entering data from other systems (e.g. scheduling systems, production data management). In fact, through the integration of multiple software it will be possible to analyse in a single simulation environment more aspects (from those technical, operational to economic ones) facilitating the integration and orchestration ability that will be obtained through the ledger implementation.

Once the connectivity has been ensured, the next step consists in the implementation of the Ledger Infrastructure, namely Synchronization services and Distributed Ledger to enable the collection and integration of information through the Cloud and to support simulation activity and what- if analysis.

The Distributed Ledger Enabler is responsible of the decentralization of the factory automation pyramid. It maintains shared process state and shared business logic on Peer Nodes that may belong to any physical Tier of the Platform (Field, Edge, Cloud), and includes all the functionality for the enablement of Ledger Services. In this case, the Synchronization Services Component is considered as an aggregation / post-processing layer that includes all smart contacts used to support the Digital Models. These smart contracts are responsible to lead the relationship between the digital model and the changes or the event that happen in the real world, namely in the shop floor.

After Ledger implementation, the smart contract instantiation and after the connection of Field abstraction with upper tier, it is possible to obtain a fully integrated CAD systems with intelligent tools for interactive design process and consequently an automatic optimization of shop floor details based on simulation services. The last component to be implemented is the Cloud infrastructure with its Open API for Virtualization that implement the cloud service endpoints. At this point a definition of maintenance plan for cloud system and a training for its utilization and management is required.

Figure 3 represents the roadmap at technical (in blue), operational (in orange) and human (in green) dimensions towards simulation and what-if analysis by means of FAR-EDGE Simulation.

The Migration Matrix in Figure 4 represents the results, in terms of digital maturity improvement, of one of the possible migration paths towards FAR-EDGE Simulation. The technical, operational and human entities most impacted by the migration towards the scenario "Simulation and What if analysis" described above are the following:

- Simulation and visualization tools that, by the implementation of the Ledger infrastructure, are able to integrate in a digital world the results of different systems, enabling the representation of virtual aspect of overall company;
- Cyber-Physical System characteristics of the process, since the processes are integrated with digital-twin capabilities to interact each other;
- Autonomous Optimization process, since each shop floor component can be abstracted, visualized and can communicate each time has impacted by condition change;
- Production IT department, since new digital systems are introduced by external experts that will also provide continuous support;
- Simulation and design employees' skills, with the first trainings focused on the use of the new technologies implemented.

VI. CONCLUSION

The FAR-EDGE migration approach shows how migration matrices can support manufacturers by providing them with a holistic view of the required steps for migration towards the Industry 4.0 vision at different dimensions of the factory, i.e. technical, operational, and human. Based on this information

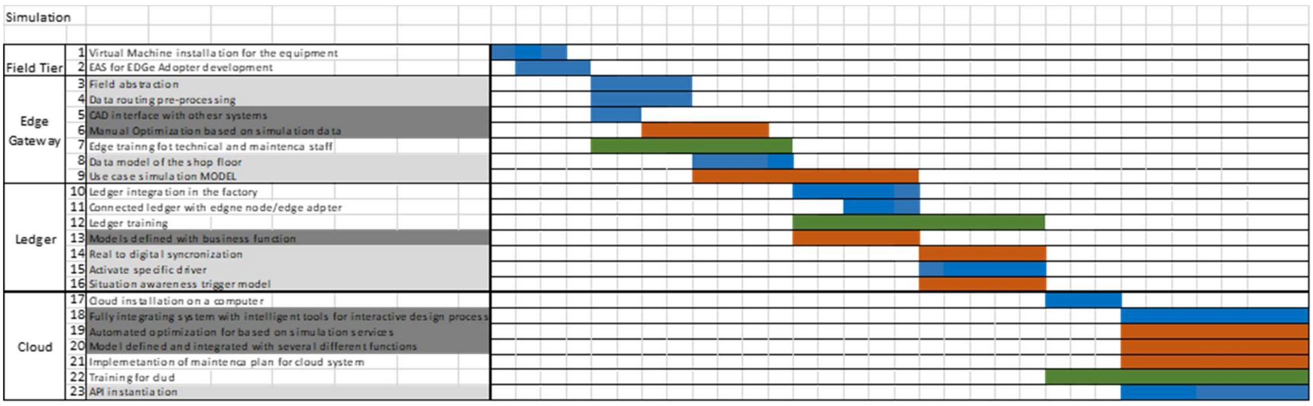

Figure 3. FAR-EDGE Simulation Roadmap for Simulation and What-If analysis scenario

MP 2 Simulation	Level 1	Level 2	Level 3	Level 4	Level 5
	3D layouts, visualization and simulation tools				
	CAD systems not related to production data	CAD systems manually feed with production data	CAD systems interfaced with other design systems	CAD systems interfaces with intelligent systems for fast development	Fully integrated CAD systems with intelligent tools for interactive design process
	Production Optimization				
	N.A.	Rare offline optimization	Offline optimization based on manual data extraction	Manual optimization based on simulation data	Automatic optimization based on simulation services
	Availability of production process models				
	N.A.	Models defined (Excel based) with limited use	Models defined with limited specific functions	Models defined and integrated with business functions	Models defined and integrated with several different functions
	Impact of digital technologies on Product Designers and Production Engineers				
	Still unclear	Identified in general terms	Analyzed	Defined	Implemented in continuous improvement

Figure 4. Migration Path (MP2) for the implementation of simulation and what-if analysis

and according to the business goals, the manufacturer can select the optimal scenario as first step of migration towards the long-term goal of complete digitalization of the factory. The solution identified within the selected scenario is then further detailed into an implementation roadmap, highlighting the necessary steps at technical, operational and human levels, in order to ensure a successful migration towards the FAR-EDGE vision.

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