Evaluation of Migration Scenarios towards Cyber-Physical Production Systems using SysML

Ambra Calà, Arndt Lüder
Otto-v.-Guericke University Magdeburg
Universitätsplatz 2. 39106
Magdeburg, Germany
{ambra.cala, arndt.lueder}@ovgu.de

Jan Vollmar, Matthias Foehr
Siemens AG Corporate Technology
Günther-Scharowsky-Str.1 91052
Erlangen, Germany
{jan.vollmar, matthias.foehr}@siemens.com

Abstract—**Over the last decades several technologies have been developed towards the distributed automation architecture for Smart Factories, however, these technologies have not been yet implemented in industry. Manufacturers are quite conservative in adopting new technologies because the vast majority of existing infrastructures already have constraints in place related to their investment capabilities and to the integration of new technologies with their legacy systems and processes. To overcome this conservatism, migration strategies and decision-making approaches are required to support industry in adopting the next generation of smart production systems step by step, taking into account not only the technical aspects, but also integrating organizational and economical issues. One essential part of these approaches is the comparative evaluation of migration options. Based on model-based systems engineering (MBSE), this paper proposes an approach that supports the evaluation of possible migration scenarios towards cyber-physical production systems (CPPS) by using the System Modeling Language (SysML).**

Keywords—cyber-physical production systems; migration strategy; model-based systems engineering; SysML.

I. INTRODUCTION

Modern markets are characterized by shorter product lifecycles, increasing product variety and shorter time-to-market. Consequently, to cope with these requirements, industries may need to adapt and reconfigure more frequently their product program and respective production systems to offer new product variants in decreasing lot-sizes, while maintaining high-quality standards and minimizing costs. Cyber-Physical Systems (CPS) technology [1] has the potential to increase efficiency in production by creating production systems that ensure [2]

- Reduced efforts for planning, engineering, installation and maintenance
- Flexible (re-) configuration
- Continuous, automatic production optimization
- Higher production system resilience
- Support of highly individualized production with small lot sizes

However, the realization of these systems in industry is very challenging. One of the major challenges is the transformation of automation architectures [2] to enable the integration of the next generation technologies.

The deployment of innovative automation technologies within decentralized control systems needs to be performed in a smooth manner taking into account the current legacy systems and processes. Therefore, a migration strategy is required to support industries to move from their legacy production systems mainly characterized by rigid centralized approach towards a cyber-physical production system (CPPS) that is dynamically adaptable to changing production environment, open to new features and functions, flexible to different processing tasks, and modular to enable quick and economical changes.

The model-based systems engineering (MBSE) has the potential to support the analysis of such complex systems through specific tools and languages, providing fully representative models of CPPS and also a holistic description of their effect on legacy production systems.

The objective of this paper is to propose elements of a methodology that supports manufacturers to identify their optimal migration path by using the graphical modeling language SysML, evaluating the possible migration options towards CPPS on the basis of predetermined selection criteria.

II. MIGRATION APPROACH

The use of new automation technologies in manufacturing will have a direct impact on the production. The migration strategy has to consider the technological innovation in the application context. In the direction of Industry 4.0 and flexible automation in production systems, the technology of CPS emerges from the incorporation of IT-based industry with engineering-based industry. Production systems will be regarded as systems integrating other systems, i.e. systems of systems. The proper use of a production system requires a proper integration of different systems, such as production technology system, the logistics system, the human machine interface system and the automation system, taking into account also their interconnections. Nevertheless, when considering the transformation of legacy production systems into cyber-physical production systems, the complexity of CPS is not the only challenging aspect.

Changes in the production process are also impacting the organizational structure, in which the involved stakeholders act, ranging from operators to engineers and companies' management. To support the systems and system-of-systems perspective, knowledge from different disciplines needs to be integrated and merged in new roles (e.g. systems engineers) [3][5]. Moreover, the success of the introduction of CPS is strongly related to the acceptance by users. The human operators need to be familiar with those systems because they

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have to take new tasks and responsibilities related to their interaction with them. Consequently, not only adequate human-machine interfaces are essential, but also education and training for the new skills [6].

In order to cope with these different challenging aspects during the definition of the system migration strategy, the production system involved in the transformation towards CPPS has to be studied as a complex socio-technical system in which the integration of new technologies and the human organization are strongly related to each other.

To this end, an instantly complete changeover of a legacy production system in one step cannot be considered also because of its negative impact in terms of high upfront investments, development time, and risk of production losses [3]. On the contrary, a stepwise migration strategy ensures low risks and immediate benefits, gradually implementing new automation systems in existing infrastructure with legacy equipment. The transformation has to be realized considering that each change may affect other systems or the system architecture, and that it is in accordance with the investment capability of the plant operator [4].

Thus, the challenge is to identify which part of the system can be migrated first and what are the possible further steps of the migration, taking into account not only the new technologies to be implemented but also the quality, organizational, social and financial aspects [7][8].

To support industry in adopting cyber-physical systems and move towards CPPS, a migration process [9] has been defined within the EU H2020 PERFoRM (Production HarmonizEd Reconfiguration of Flexible Robots and Machinery) project [10].

The proposed process follows the lean and agile ideas [11] in order to support the continuous improvement, adaptation and innovation of a system when the way forward and target conditions are unclear and uncertain. The objective of the migration process, thus, is to define the general suitable path towards the long-term vision that, step-by-step, reaches a set of short-term goals using an identified sequence of migration steps for each of the goals (see Figure 1).

The long-term vision (Figure 1-a) represents the target production system (e.g. CPPS) that the manufacturer intends to achieve in the long run, following the company strategy. Since the migration path to go from the current situation to the long-term vision is uncertain, it can be decomposed in a number of stages and migration steps in order to mitigate possible risks and obstacles. As depicted in Figure 1-b, the possible solutions to achieve the first short-term goal, thus the first migration steps, can be identified at the beginning while the solutions to perform the next steps will be still uncertain.

These solution options need to be carefully investigated taking into account different decision aspects at each step. The selected ones need to be tested and, if needed, changed and analyzed again before implemented (Figure 1-c). Once the first migration is performed, the characteristics of the production system will be changed and a new analysis of possible solution options for the next steps will be identified and evaluated again (Figure 1-d). In this way, the production system will be smoothly transformed at each step by implementing one-by-one new components and new features.

As the system is gradually transformed in the direction of the long-term vision, the identification of new possible solutions to be implemented will be easier. The succession of these steps constitutes the migration path to achieve the final goal (Figure 1-e).

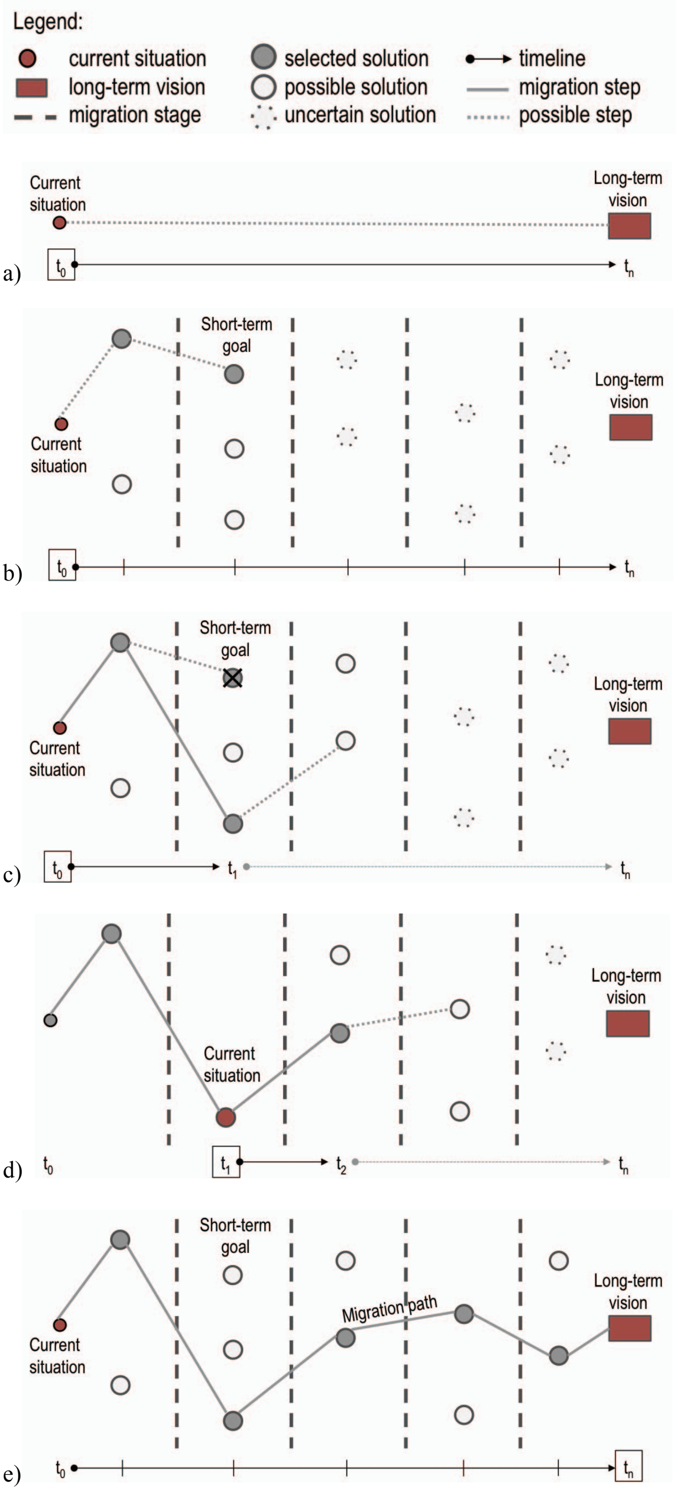

Figure 1: Definition of the migration path

The 5-phases general migration process developed within the PERFoRM project (Figure 2) intends to support this stepwise and continuous migration to a more flexible, intelligent and innovative system by breaking down the path towards the long-term vision in migration solution steps that are identified, designed and executed following the described iterative and incremental approach.

The process starts with the *Preparation* phase where the existing system is analyzed and the long-term vision, namely the target system to which the current one is going to be migrated, is defined (Figure 1-a). In the *Options Investigation* phase different migration solutions are collected and evaluated, in order to identify the optimal migration steps towards the target system (Figure 1-b). The selected solution option is then detailed within the *Design* phase, in which the new systems and their integration with the legacy systems are defined. After the feasibility of the designed solution is tested, see Figure 1-c, it can be implemented and verified within the *Implementation* phase. In the *Deployment* phase the installed system is commissioned and validated, transforming the considered production system (Figure 1-d). Once the first step of migration is performed it is possible to start again from the Preparation phase, analyzing the new “current” situation of the system, to define the next migration steps until the target system is fully implemented (Figure 1-e).

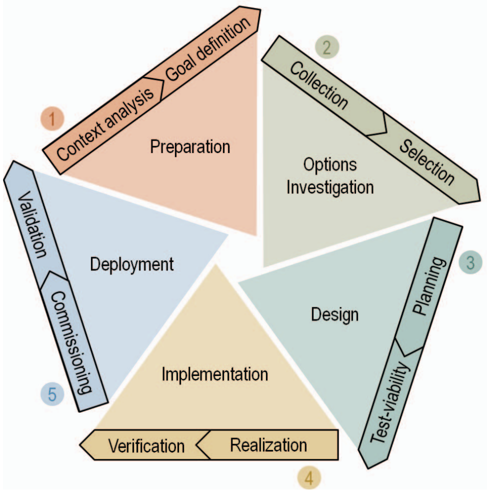

Figure 2: Migration process [9]

III. A DECISION-MAKING PROBLEM

A key element of the migration process is the Options Investigation phase, with the assessment and selection of migration-step alternatives. The identification of the optimal migration path for the considered production system is a big challenge. In order to successfully deploy CPPS concepts, adding value at each migration-step and supporting the achievement of the long-term goal, different aspects need to be considered [12]. The implementation of smart devices, intelligent systems and new communication protocols has a big impact not only on the technological dimension of the factory but also on system’s performance, work organization, and business strategy [13].

To identify how a transformation solution towards cyber-physical production systems affects the overall production system and its subsystems all these aspects need to be considered together and simultaneously in a holistic approach. Therefore, a decision-making approach is necessary to evaluate the different production system improvements by comparing various criteria and ranking the alternatives with regard to the decision maker's goals and needs defined in the Preparation phase.

IV. EVALUATION APPROACH FOR MIGRATION OPTIONS

The multi-disciplinary model-based systems engineering (MBSE) approach has been increasingly adopted for development support in manufacturing processes [14], especially in the direction of CPPS [15][16], the Smart Factory vision [17], modernization processes [18], and many others. Model-based approaches have the potential to assist the transformation of traditional production systems into CPPS covering different aspects of the new solutions, from the business requirements definition to the design and simulation of the target system.

The MBSE has been considered within this research to describe how the integration of new complex systems, such as cyber-physical production systems, impact on the legacy equipment at architectural and system levels, i.e. representing where an adaptor is required in order to enable the communication between the systems and what new skills a human operator should have to use or maintain the new implemented systems.

The proposed approach is inspired by the modularity considerations within product engineering discussed by Eppinger & Pimmler [19] and Schlund & Winzer [20].

Especially, following the MBSE approach, it provides a perception of the impact of possible new solutions on the existing system, in terms of technologies and tasks of both systems and human operators, through the modeling of system solutions using the System Modeling Language (SysML), which is used here to graphically represent different migration scenarios towards CPPS.

SysML provides a good basis to holistically evaluate the migration options under different aspects, modeling the system as it is now and how it will look like if new technologies and applications are implemented, according to the considered possible solutions. To this end, SysML block diagrams and activity diagrams are used to depict the internal structure of the solution system and the behavior of the respective entities involved in each migration scenario.

In particular, structure and interactions between these blocks in a migration scenario are represented by Internal Block Diagrams (IBD), in which the flow ports represent the physical or data interfaces and the connectors can give indications on the type of communication exchange.

The Activity Diagrams (AD) describe the behavior of each system and especially of the human operators that have a role in the considered migration scenario. Principally, ADs are used to identify new skills and roles of human operators required by the usability and maintainability of the new-implemented systems.

Within the context of a production system that migrates towards CPPS integrating new technologies with the equipment already in place the system entities of a migration scenario, depicted as blocks in IBDs, represent legacy systems, new systems and human operators, while the actions defined in ADs describe the behavior of old and new systems and the tasks of human operators. In order to provide an overview of the new solution's impact on the considered production system, the category to which each system entity belongs is marked using the stereotype <<legacy>>, <<human>>, or <<new>>. To better highlight this distinction, the legacy systems and human operators' blocks and activities are colored in grey, while the changes and new tasks that need to be performed by existing entities, i.e. human operators and new interfaces on existing blocks, are depicted in yellow. New systems blocks and their activities are colored in green.

The impact of the proposed migration solution on the existing system is emphasized in the SysML diagrams by the use of different colors. In addition to grey for legacy systems, yellow for modified ones and green for the new ones, other colors can be also considered, e.g., it might be necessary to represent also the entities that are not going to be used anymore in the new solution.

This colored representation of the migration scenarios provides an immediate overview on the impact of system changes at technological, operational and human levels. Moreover, additional information can be assigned to the blocks showing the main characteristics of the entities, needed to evaluate the impact aspects of each of these migration configurations. Impact aspects can be related to the performance indicators of the new systems, such as implementation time, systems integration, maintainability, IT security, costs of new technologies, return on investments, and others. The selection of the optimal scenario depends on the number of the involved entities, the interconnection between them, and the relevant aspects of impacts of the production system, as well as the consistency of the achieved results with the long-term vision of the factory. Nevertheless, typically the ratio of costs and benefits shall be at least positive to convince the decision makers. On the other hand, other indicators can be more relevant, depending on the business strategy of the company.

V. EXAMPLE OF APPLICATION

The industrial application example provided here describes a simple scenario in an automotive factory. The manufacturer aims to introduce cyber-physical system concepts in his factory to support individualized production with small lot sizes and, at the same time, to minimize costs and waste of productivity. One of the most important causes of productivity losses of the factory is the unplanned malfunction of machinery resulting in delivery delays and costs associated to equipment downtime. Whenever a robot or machine fails, the production line stops until the problem is manually resolved or the machine is exchanged.

The case study focuses on the possible first migration step aiming at the reduction of production downtime in assembly cells of the current car body production line, decentralizing the control architecture. For simplicity only two migration scenarios are represented in Figure 3 and 4 at architectural level. However, once the blocks and their characteristics are defined and "stored" in the model repository, it is possible to consider also alternative configurations of the two scenarios in order to identify the optimal one for the considered migration step.

The first migration scenario "A" proposes the implementation of plug-and-produce capabilities for the fast reconfiguration of the assembly line in case of failures. First requirement is the provision of plug-and-produce adapters that enable the mechanical and electrical connection of the assembly robots that need also to communicate to the scheduling system via web services interfaces. To realize this scenario the human operator should be trained in order to be qualified for the physical and electrical connection control.

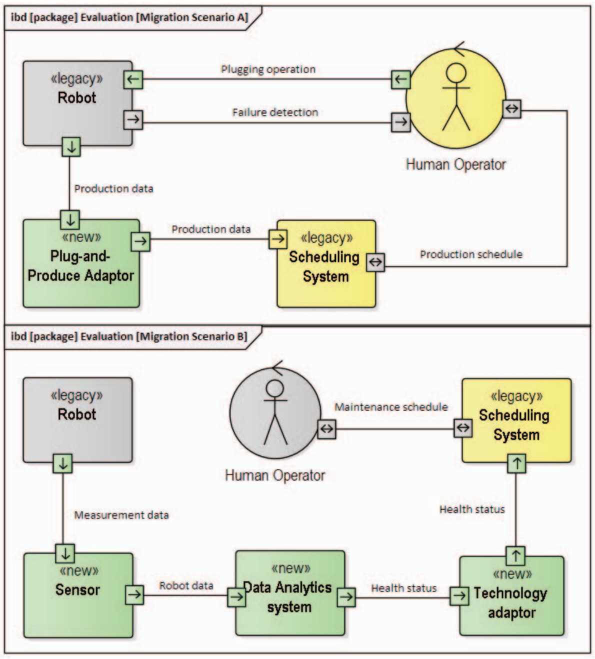

Figure 3: Internal Block Diagrams of migration scenarios

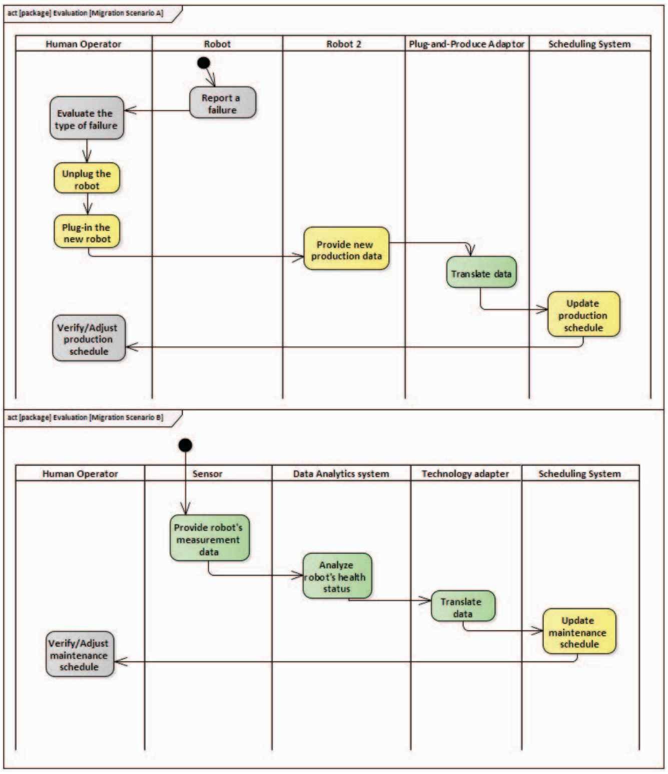

Figure 4: Activity Diagram of migration scenarios

Another possible improvement step is the second scenario "B" that consists on the implementation of self-monitoring capabilities of assembly machines, which helps to extend machines operating life by revealing degradation of production quality and wear of tools, or other problems. The machines will need additional sensors to acquire relevant data for condition monitoring systems, on the other hand the access to machine health information at factory level will successively allow operators to optimize maintenance schedules and increase uptime.

Moreover, a combination of both migration scenarios "A" and "B" can be evaluated, i.e. migration scenario "C".

The comparison of the migration scenarios is shown in the Block Definition Diagram depicted in Figure 5, in which the main impact aspects (implementation costs, productivity, downtime), defined during the preparation phase of the migration process, are estimated based on the information contained in the solutions models. This representation creates a solid baseline for further trade-off analysis of the migration options to identify the added value they can bring to the production system and, consequently, the optimal migration solution. Functions for costs or production time evaluation can also be modeled using Parametric Diagrams.

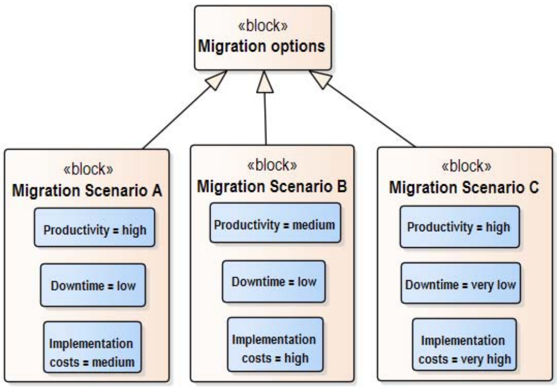

Figure 5: Block Definition Diagram for Trade-off analysis

VI. CONCLUSIONS

The migration from traditional towards cyber-physical production systems implicates technological, organizational and economic considerations, especially in terms of integration of the next-generation technologies and applications with legacy equipment and human operators.

This paper proposes an approach to evaluate different migration scenarios that enable the transformation of existing production systems towards CPPS. The migration alternatives representation in SysML shows how the system conditions change with the introduction of new technologies. The diagrams help to identify not only all the required interfaces to integrate the new systems but also the human skills required to perform the new operational scenario. Moreover, MBSE supports the trade-off study to compare the impact aspects of the different migration options. The model can be further detailed accordingly to the different stakeholders' perspectives, representing the components structure of the new system for the physical implementation, the human organization structure or the costs-benefits dependencies. Another advantage of this approach is the reusability of the modeled migration options and technology blocks for further migration steps, supporting the iterative migration process, or even for different use cases.

ACKNOWLEDGMENT

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

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