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A Structured Migration Framework for Brownfield Digital Transformation in Manufacturing Systems

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ABSTRACT

The digital transformation of manufacturing enterprises poses significant challenges, especially in existing brownfield production environments Legacy production infrastructures are often characterized by heterogeneous automation systems, proprietary communication interfaces, and inconsistent data models, limiting interoperability between machines, IT systems, and digital services. At the same time, companies must maintain the operation of existing production assets while gradually integrating them into modern, data-driven value creation networks. Although numerous Industry 4.0 reference architectures, standards, and technologies—including the Reference Architectural Model Industry 4.0 (RAMI 4.0), the Industrial Internet Reference Architecture (IIRA), the Asset Administration Shell (AAS), OPC UA, Companion Specifications, and Digital Twins—provide essential building blocks for digitalization, they are typically considered in isolation. This paper investigates how these complementary concepts can be combined into a structured migration framework for Brownfield production environments. The proposed approach analyzes relevant reference architectures, communication standards, and semantic information models, categorizes them according to their functional roles, and describes their interaction within a stepwise migration process toward interoperable Smart Factory architectures. To illustrate the framework, the Smart Factory research and demonstration environment at Bochum University of Applied Sciences is used as a case study. The implementation examines how established Industry 4.0 reference architectures, standards, and enabling technologies can be systematically combined to support the structured digital transformation of existing Brownfield production systems.

Keywords: Brownfield manufacturing, Industry 4.0, Smart factory, Reference architectures, Digital transformation framework, Industrial interoperability

INTRODUCTION

Manufacturing companies are currently undergoing the fourth industrial revolution, in which digitalization and smart manufacturing have become key enablers for maintaining competitiveness. Increasing customer demand, growing product complexity, and the need for flexible production systems are driving the integration of digital technologies into

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manufacturing environments. In this context, cyber-physical systems (CPS), the Industrial Internet of Things (IIoT), and interconnected production assets continuously generate and exchange data, enabling real-time monitoring, optimization, and autonomous decision-making across production processes (Wee et al., 2016; Capgemini, 2023). By transforming machine data into actionable information, digital manufacturing not only improves operational efficiency but also enables data-driven services, innovative business models, and highly customized production (Fraunhofer, 2020). Consequently, digital transformation has evolved from a technological trend into a strategic necessity for manufacturing companies seeking to remain competitive in an increasingly connected industrial landscape. Despite these opportunities, the digital transformation of manufacturing remains particularly challenging in Brownfield production environments, where existing production systems have evolved over decades. These environments typically consist of heterogeneous machine parks comprising equipment from different manufacturers, generations, and automation levels. As a result, a wide variety of communication protocols, proprietary interfaces, and control systems coexist, while standardized data models and semantic interoperability are often missing. Integrating such legacy equipment into modern IIoT architectures therefore requires overcoming significant technical challenges related to connectivity, data acquisition, and information exchange. Furthermore, the increasing interconnection of production assets substantially raises the complexity of industrial communication networks, leading to higher coordination efforts as well as increased requirements for cybersecurity and system reliability (Wee et al., 2016). Although large enterprises have already initiated comprehensive Industry 4.0 programs, many small and medium-sized enterprises (SMEs) still face considerable uncertainty regarding the practical implementation of digital transformation, mainly due to the complexity of their existing Brownfield infrastructures (Lichtblau et al., 2015). To address these challenges, numerous reference architectures, communication standards, and digitalization technologies have been proposed for Industry 4.0. Frameworks such as RAMI 4.0, IIRA, and ISA-95 support the design of interoperable manufacturing architectures, while technologies including OPC UA, MQTT, and the Asset Administration Shell (AAS) enable standardized communication and semantic interoperability. However, these approaches mainly address individual aspects of digital transformation and provide limited guidance on how they can be systematically combined to support the migration of existing Brownfield production systems. Consequently, a structured framework that integrates these complementary concepts into a coherent migration process remains missing (Lichtblau et al., 2015; Hartner et al., 2020). This paper contributes by analyzing existing Industry 4.0 reference architectures, standards, and enabling technologies and proposing a structured migration framework for Brownfield manufacturing systems. Based on the Smart Factory Demonstrator at Bochum University of Applied Sciences, the framework investigates how RAMI 4.0, IIRA, ISA-95, AAS, and OPC UA can be combined to support the incremental transformation of legacy production systems into interoperable Smart Factory architectures.

RESEARCH BACKGROUND AND RELATED WORK

This chapter presents the theoretical foundations of brownfield digitization in the context of Industry 4.0. To this end, the relevant reference architectures, standardization approaches, and key technologies for digital transformation are analyzed and described. Finally, the concepts relevant to this work are classified according to their functional role and their contribution to the phased digitization of existing production facilities.

Smart Factory The Smart Factory describes the vision of an intelligent, networked, and adaptive production environment in the context of Industry 4.0. In contrast to traditional production systems, which are characterized by centrally controlled processes and isolated information structures, the Smart Factory is based on the end-to-end networking of production facilities, information systems, products, and people. The goal is flexible and efficient production in which processes can be largely self-organized, data-driven, and automated using digital technologies. Cyber-physical systems (CPS) form a central foundation of the Smart Factory, establishing the connection between the physical production environment and digital information systems. Through sensor technology, embedded systems, and industrial communication networks, production facilities are continuously supplied with data, thereby enabling the creation of digital representations of real-world objects. These digital representations form the basis for data-driven analyses, optimizations, and intelligent decision-making processes within modern production systems. A key prerequisite for implementing a Smart Factory is the collection and processing of extensive production data. With sensors, Industrial Internet of Things (IIoT) technologies, and modern communication solutions, relevant process, machine, and status data are captured in real time (Soori et al., 2023). This data is increasingly processed through a combination of edge computing and cloud computing, enabling both rapid local processing and higher-level analysis of large data sets. Methods from the fields of data analytics and artificial intelligence support the identification of patterns, the prediction of future states, and the optimization of production processes. However, implementing a smart factory requires not only technological innovations but also a gradual transformation of existing production structures. In brownfield environments particularly, the integration of legacy machinery, heterogeneous automation systems, and proprietary interfaces poses a major challenge. The transition to a smart factory therefore cannot be achieved through a complete overhaul of existing facilities but requires structured transformation paths that gradually enhance existing systems with digital technologies (Etz et al., 2020; Soori et al., 2023; Lee et al., 2017; Figueredo Rocha, 2023).

Greenfield and Brownfield Approaches in Industrial Digitalization In the context of the digital transformation of industrial production systems, a fundamental distinction is made between greenfield and brownfield approaches. The greenfield approach involves the complete redevelopment of a production environment without taking existing structures or technical constraints into account. All equipment, automation systems, IT infrastructures, and processes are planned and implemented from the ground up. This provides a high degree of freedom of design, allowing

modern technologies, standardized communication architectures, and Industry 4.0 concepts to be integrated from the very beginning. In particular, the implementation of consistent data structures and interoperable system architectures is easier to achieve in greenfield projects, as there is no need to account for legacy system boundaries or proprietary interfaces. Despite these advantages, greenfield projects present significant challenges. In addition to high investment costs, they involve lengthy planning and implementation periods, as entire production systems must be rebuilt and organizational processes adapted. For many manufacturing companies, this approach is therefore only feasible to a limited extent due to existing production requirements, high asset values, and the need for existing manufacturing systems to remain available (Wischhusen, 2023; Etz et al., 2020). The brownfield approach, on the other hand, focuses on the gradual modernization and expansion of existing production environments. In this process, existing machinery, automation systems, and infrastructure continue to be used and are strategically supplemented with new digital technologies. The goal is not to completely replace existing production facilities, but rather to expand their functionality through digitization, networking, and intelligent information processing. This approach matters especially for established manufacturing companies, as facilities have often evolved over many years, and a complete overhaul would be neither economically nor technically feasible. A key challenge of brownfield digitization lies in the heterogeneity of production systems that have evolved. Different machine manufacturers, proprietary communication interfaces, inconsistent data structures, and a lack of semantic descriptions complicate the integration of modern Industry 4.0 technologies. Existing plants often lack standardized interfaces or digital representations, making direct integration into modern IT and data architecture difficult. In addition to technical challenges, companies also face organizational and economic issues. The adoption of digital technologies requires skilled workers, investments in IT and automation infrastructure, and adjustments to existing work and process structures. Small and medium-sized enterprises face the challenge of using limited resources efficiently while simultaneously realizing the benefits of digital technologies. In addition, aspects such as cybersecurity, data protection, and the acceptance of new digital ways of working must be considered (Wischhusen, 2023; Etz et al., 2020).

Migration Approaches and Industry 4.0 Reference Frameworks

Automation Pyramid/ISA-95 (International Standard IEC 62264) The automation pyramid is considered a fundamental concept in industrial manufacturing control systems. It provides a structured view of the various technologies and systems used in a production environment. This pyramid divides automation into hierarchical layers, starting with field and process automation at the lowest level and extending up to enterprise management and planning at the top. This hierarchical structure helps organize and understand the complexity of automation. Each level plays a crucial role and is entrusted with specific tasks and functions. It should be noted,

however, that in practical operations, the boundaries between the levels are often fluid, depending on the individual requirements and circumstances of a manufacturing facility. In this context, the automation pyramid is an indispensable tool for effectively structuring and controlling automation processes in the modern manufacturing industry (Kobbert, 2026; Sánchezet al., 2023).

Reference Architecture Frameworks: RAMI 4.0 and IIRA The Industry 4.0 Reference Architectural Model (RAMI 4.0) is a central architectural model for structuring and describing Industry 4.0 systems. It was developed to organize the various technical, organizational, and information technology levels of networked production systems within a common reference framework. RAMI 4.0 combines three key dimensions: the hierarchical levels of industrial systems, the functional layers of a system, and the lifecycle and value chain of an asset. In the context of brownfield digitization, RAMI 4.0 specifically supports the structured analysis of existing production facilities and their step-by-step integration into Industry 4.0 architecture. Existing machines and systems can be classified using the model and evaluated in terms of their digitization potential. RAMI 4.0 does not serve as a ready-made implementation concept, but rather as a framework that enables the description of Industry 4.0 components and serves as a basis for selecting suitable technologies and standards. RAMI 4.0 is of significant importance due to its ability to link physical assets with digital representations. This connection forms the basis for concepts such as Asset Administration Shell and enables the standardized integration of existing production components into future smart factory environments (Plattform Industrie 4.0, 2022; Stock, 2020).

Industrial Internet Reference Architecture (IIRA) The Industrial Internet Reference Architecture (IIRA) is a reference model for industrial Internet of Things (IIoT) systems and takes a system-oriented approach to describing complex industrial applications. Unlike RAMI 4.0, which is specifically tailored to the requirements of Industry 4.0 and manufacturing systems, IIRA considers industrial IoT systems across all industries. IIRA structures industrial systems through various architectural perspectives, including the Business View, Usage View, Functional View, and Implementation View. These perspectives enable a holistic view of business requirements, system functions, technical components, and their implementation. By breaking down complex systems into functional components, IIRA supports the planning and design of scalable industrial IoT architecture. In the context of brownfield digitization, IIRA provides a methodological framework for analyzing existing production environments and integrating heterogeneous systems into industrial IoT architectures. Of relevance here is the consideration of data flows, system boundaries, and integration points between production facilities, IT systems, and digital services. While RAMI 4.0 primarily supports the structuring of Industry 4.0 components and production systems, IIRA provides a more comprehensive architectural approach for the design of industrial IoT systems. Both reference architectures can therefore be viewed as complementary approaches that offer different perspectives on the digital transformation of existing production environments (Plattform Industrie 4.0, 2022; Stock, 2020).

Smart Manufacturing Reference Model/ IEC 63339 IEC 63339 marked the first development of an internationally standardized Smart Manufacturing Reference Model (SMRM) that provides a uniform framework for modeling smart manufacturing systems. Unlike reference architectures such as RAMI 4.0 or IIRA, IEC 63339 does not define a specific system architecture or implementation but rather describes a high-level reference model for the structured development and specialization of further smart manufacturing models. To this end, the reference model introduces a unified terminology, fundamental modeling elements, their relationships, and conformity criteria. It considers products, equipment, and services, as well as their respective life cycles. The goal is to establish a common understanding of the key entities of smart manufacturing systems and thereby support the development of interoperable standards and domain-specific reference models. A key contribution of IEC 63339 is that it brings together various aspects of smart manufacturing within a common modeling framework. This allows existing reference architectures and future extensions to be described consistently and organized in terms of their relationships to one another. This facilitates the analysis of complex manufacturing systems as well as the integration of new technologies into existing production environments. However, for the digital transformation of brownfield manufacturing facilities, IEC 63339 itself does not provide a concrete procedural model for migrating existing production systems. Rather, it provides a conceptual modeling framework that supports the development of interoperable smart manufacturing solutions and can serve as a basis for describing and harmonizing various Industry 4.0 concepts (VDE, 2024).

Information Model: Asset Administration Shell (AAS) The Asset Administration Shell (AAS) is a central component of the Industry 4.0 architecture and serves as a standardized digital representation of a physical or logical asset. Unlike reference architectures such as the Reference Architectural Model for Industry 4.0 (RAMI 4.0), which describes the structural design of Industry 4.0 systems, the AAS provides a standardized information model that digitally maps the characteristics and capabilities of an individual asset (Plattform Industrie 4.0, 2022; Stock, 2020). The goal is to provide information in a uniform and interoperable format, independent of manufacturers and proprietary systems. Within the AAS, all relevant information about an asset is organized into standardized submodels. In the context of brownfield digitization, the AAS plays a key role in the semantic integration of existing production facilities. While communication standards such as OPC UA enable interoperable data exchange between systems, the Asset Administration Shell establishes a uniform understanding of the information provided. This allows heterogeneous machines and systems from different manufacturers to be described in a standardized manner, linked together, and gradually integrated into Industry 4.0-compliant production environments. The AAS thus forms the foundation for advanced concepts such as digital twins, data-driven services, and the integration of existing production facilities into networked smart factory and Manufacturing X ecosystems.

Maturity Models

Maturity models provide an important framework for planning and evaluating digitalization projects. Unlike reference architectures, communication standards, or information models, they do not describe technical implementation but rather serve to systematically assess the current level of digitalization of a company or production system. Based on this assessment, areas for action can be identified and appropriate transformation measures prioritized. Particularly in the context of brownfield digitalization, maturity models help companies design the transition from existing production facilities to Industry 4.0-compliant production systems in a step-by-step and targeted manner (Schuh et al., 2017; Weber et al., 2017; Lee et al., 2017).

Enabling Communication Technologies

OPC UA OPC Unified Architecture (OPC UA) is an internationally established communication standard developed by the OPC Foundation for secure, platform-independent, and interoperable data exchange in industrial automation systems. Beyond data transmission, OPC UA provides an object-oriented information model that enables the structured description of data and its meaning. Therefore, it supports cross-vendor interoperability between machines, controllers, and higher-level IT systems. Within Brownfield digitalization, OPC UA serves as an integration layer that connects heterogeneous production systems with Industry 4.0 applications without requiring major modifications to existing equipment. In combination with Companion Specifications and the Asset Administration Shell, OPC UA enables both standardized communication and semantic interoperability, supporting the incremental migration toward Smart Factory architectures (Silveira et al., 2019; Hunkeler et al., 2008; OPC Foundation, 2022).

MQTT Message Queuing Telemetry Transport (MQTT) is a lightweight publish/subscribe communication protocol designed for efficient data exchange in resource-constrained and distributed environments. In Brownfield digitalization, MQTT is commonly used to transfer sensor, machine, and status data between production systems, edge devices, and cloud-based applications. Unlike OPC UA, MQTT does not provide semantic information models but focuses on scalable message transport. Therefore, it is often combined with technologies such as OPC UA or the Asset Administration Shell to enable both efficient data distribution and standardized information representation within Industry 4.0 architectures (Silveira et al., 2019; Hunkeler et al., 2008; OPC Foundation, 2022).

Research Application at Bochum Smart Factory Environment

The practical implementation of the digital transformation of existing production systems presents manufacturing companies with the challenge of gradually transitioning legacy systems into modern Industry 4.0 architectures. Particularly in brownfield production environments, a complete replacement of existing machines and automation systems is often not feasible due to economic, technical, and organizational constraints. Instead, the transformation

requires a structured approach that preserves existing production resources and gradually expands them using standardized communication, information, and automation technologies. Against this backdrop, our research approach at Bochum University of Applied Sciences examines a Structured Migration Framework that describes a systematic migration strategy for the digitalization of brownfield production environments. The framework combines the analysis of existing production systems, the definition of a target architecture, and the step-by-step integration of suitable Industry 4.0 reference architectures, communication standards, and information models into a consistent transformation process. The goal is to demonstrate, particularly to small and medium-sized enterprises (SMEs), a practical and economically feasible path toward the gradual digitization of existing production facilities. The Smart Factory Demonstrator at Bochum University of Applied Sciences serves as a research and demonstration environment for investigating and validating this approach. The modular production environment represents a typical brownfield manufacturing landscape with heterogeneous production and logistics systems of different generations and varying degrees of integration. As part of the research, existing production modules are gradually enhanced with Industry 4.0 technologies and integrated into a shared digital infrastructure. To this end, reference architectures, standardized communication protocols, and semantic information models are combined to ensure interoperability between machines, IT systems, and digital services. Using the research environment, the study demonstrates how theoretical reference models and standardization concepts can be applied in a realistic brownfield production environment and how their structured interaction supports the gradual transformation of existing production systems into a smart factory. The first step involves analyzing the existing production environment and identifying available resources, interfaces, and data sources. This requires evaluating existing machines, control systems, and automation components in terms of their integration capabilities. In the Smart Factory Demonstrator, this applies to the existing PLC systems, robotic units, and automated stations, which were originally operated independently of one another. Since brownfield facilities are typically characterized by heterogeneous system landscapes involving different manufacturers, communication protocols, and data structures, establishing a seamless digital connection poses a major challenge. The existing production modules are therefore not replaced but rather expanded with additional digital interfaces. This approach enables a phased migration in which existing plant functions are retained while new digital capabilities are added. Following an analysis of the existing infrastructure, the production components are gradually connected digitally. To this end, various stations of the Smart Factory Demonstrator were supplemented with IoT components and microcontroller-based extensions. These serve as digital interfaces between the physical production level and higher-level information systems. For example, production modules have been expanded with Raspberry Pi-based communication solutions to exchange signals between digital applications and existing automation components. This makes it possible, among other things, to transmit control information such as start and stop signals to robotic systems without having to fundamentally change the existing control

structure. Established Industry 4.0 technologies are used for communication between the individual components. OPC UA enables structured communication between industrial automation systems, while MQTT is used as a lightweight communication protocol for the flexible transmission of IoT and machine data. Through this communication layer, previously isolated production components are gradually integrated into a shared digital infrastructure. However, as connectivity increases, additional requirements arise regarding cybersecurity, network segmentation, and access control. A brownfield migration must therefore take security aspects into account in addition to technical integration to ensure the long-term availability and integrity of industrial production systems. Once digital connectivity has been established, the structured collection and processing of production data constitute the next stage of the migration. A major challenge with existing production systems is that, although large amounts of machine data are available, this data is often not uniformly structured or in a format suitable for analysis. In the Smart Factory Demonstrator, a central data infrastructure was therefore established to consolidate production and machine data from various systems. To this end, a database server was implemented as a central communication and information platform. This allows the collected data to be processed independently of the original machine structure and made available for further applications. A key component of this transformation was the processing of extensive PLC data. Initially, approximately 15,000 signals were collected from various production systems. This dataset was then evaluated and reduced to identify relevant process and status information for further applications. This data processing transforms raw machine signals into actionable information, which forms the basis for data-driven production optimizations. This step involves transitioning from a traditional automation structure to a data-oriented smart factory architecture. The establishment of a manufacturing data platform creates a unified data foundation that serves as the basis for interoperable information flows and supports the implementation of reference architectures such as RAMI 4.0 and ISA-95. Building on the central data platform, digital value-added services can be developed to increase production transparency and efficiency. In the Smart Factory Demonstrator, an edge-cloud application was implemented for this purpose, which aggregates production and machine data from various systems and, in the future, will enable the integration of multiple smart factory environments. Various analytics and visualization applications have already been implemented based on this infrastructure. These include dashboards for displaying production statuses as well as analyses of operation and downtime. In addition, maintenance intervals are being examined, and initial approaches for predictive maintenance applications are being developed. These applications facilitate a transformation from purely reactive production monitoring to data-driven operations management. The information gathered enables early detection of plant conditions and lays the foundation for future optimization processes. Another stage of development within the transformation architecture is the creation of digital twins for individual production modules. While previous data integration primarily enabled the collection and processing of machine data, digital twins create a structured digital representation of physical production resources. An extension via Asset

Administration Shell (AAS) enables a standardized description of Industry 4.0 components. This allows information about machines, modules, and production resources to be made available independently of proprietary system boundaries. The combination of digital twins and standardized information models thus creates a foundation for an interoperable smart factory architecture. Based on the communication and data infrastructure that has been established, additional intelligent functions can be integrated step by step. The current development focuses on integrating AI applications into existing legacy systems through containerized deployment, enabling flexible extension of production capabilities without replacing existing automation structures. Future enhancements include the integration of autonomous mobile robots (AMRs), supported by the existing data infrastructure for production status, material flow, and warehouse information. Additionally, smart energy components such as digital meters and switching elements are being integrated to enable energy monitoring and support optimized production processes.

CONCLUSION

The proposed Incremental Data-Centric Brownfield Migration Approach investigates how complementary Industry 4.0 reference architectures and standards can be combined to support the structured transformation of existing manufacturing systems. Instead of applying individual frameworks separately, the approach integrates RAMI 4.0, ISA-95, and IIRA to address different perspectives of the migration process. RAMI 4.0 provides the architectural structure for assets, information, and functions, ISA-95 supports the integration of production and enterprise systems, and IIRA contributes a system-level perspective on business, functional, and implementation aspects. The framework follows a data-centric migration strategy in which existing production assets are first connected through standardized communication interfaces and integrated into a common data infrastructure. Based on this foundation, higher-level Industry 4.0 applications such as analytics, digital twins, Asset Administration Shells, and AI-based services can be incrementally introduced. The implementation within the Smart Factory Demonstrator confirms that a structured Brownfield digital transformation should be regarded as a continuous migration process rather than a one-time modernization project. By combining interoperable technologies, standardized information models, and reference architectures, existing production systems can be gradually transformed into scalable Smart Factory architectures while maintaining existing investments.

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