Remote integration of advanced manufacturing technologies into production systems: integration processes, key challenges and mitigation actions

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Abstract

Purpose – The study examines the remote integration process of advanced manufacturing technology (AMT) into the production system and identifies key challenges and mitigating actions for a smoother introduction and integration process.

Design/methodology/approach – The study adopts a case study approach to a cyber-physical production system at an industrial technology center using a mobile robot as an AMT.

Findings – By applying the plug-and-produce concept, the study exemplifies an AMT's remote integration process into a cyber-physical production system in nine steps. Eleven key challenges and twelve mitigation actions for remote integration are described based on technology–organization–environment theory. Finally, a remote integration framework is proposed to facilitate AMT integration into production systems.

Practical implications – The study presents results purely from a practical perspective, which could reduce dilemmas in early decision-making related to smart production. The proposed framework can improve flexibility and decrease the time needed to configure new AMTs in existing production systems.

Originality/value – The area of remote integration for AMT has not been addressed in depth before. The consequences of lacking in-depth studies for remote integration imply that current implementation processes do not match the needs and the existing situation in the industry and often underestimate the complexity of considering both technological and organizational issues. The new integrated framework can already be deployed by industry professionals in their efforts to integrate new technologies with shorter time to volume and increased quality but also as a means for training employees in critical competencies required for remote integration.

Keywords Technology adoption, Industry 4.0 implementation, Cyber-physical production system, Plug and produce, Smart production, Mobile robot, TOE framework, Production system development, Process innovation, Technology integration

Paper type Case study

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1. Introduction

Adapting to product variants in today's highly automized production systems is usually costly. The ability to constantly adjust and adapt the production system is a major determinant for competitive and sustainable customer-order-driven production (Narain *et al.*, 2000; Bellgran and Säfsten, 2010; Wang and Zhang, 2022). In this regard, literature has explored the development of flexible and reconfigurable production systems (ElMaraghy, 2005; Mehrabi *et al.*, 2002; Rösiö and Bruch, 2018; Eynaud *et al.*, 2021).

Yet many companies still find it challenging to integrate new advanced manufacturing technologies (AMT) and devices into production systems (Abd Rahman and Bennett, 2009) due to problems such as the systems' high interdependencies and systematic nature. Specifically, a change in one part of the production system affects other subsystems and processes (Bruch and Bellgran, 2014; Díaz-Reza *et al.*, 2020). AMT integration is also affected by the degree of newness (Tatikonda and Rosenthal, 2000; Chirumalla, 2018) where the manufacturing company has poor knowledge and could affect technology-related planning, organization and management (Sambasivarao and Deshmukh, 1995; Stornelli *et al.*, 2021). For example, Chaoji and Martinsuo (2019) revealed the need for different creation processes, roles and interactive activities for different types of radical manufacturing technology innovations. Thus, AMT integration is characterized as technically difficult, organizationally complex and problematic (Sjödin *et al.*, 2018), leading to quality differences and cost variations.

Digitalization, a main potential driver for advanced manufacturing, is closely linked to Industry 4.0 digital technologies (i.e. combinations of information, computing, communication and connectivity technologies) (Bharadwaj *et al.*, 2013), such as the Internet of things (IoT), artificial intelligence (AI), cloud computing, big data technologies, blockchain, augmented reality, automation, advanced robotics, additive manufacturing, simulation and semantic technologies (e.g. Rad *et al.*, 2022). By continually adjusting and optimizing production processes online, digital technologies aim to improve processes' flexibility and reliability and improve product quality and maintenance practices in industrial firms (Chirumalla, 2021).

One of the greater potentials of advanced digital technologies applied in manufacturing is the possibility of providing remote access and integration into physical production systems. Considering the current pandemic crisis, remote access and integration using AMTs will offer unique opportunities and capabilities for manufacturing industries, especially cyber-physical production systems (e.g. Liu *et al.*, 2020; Jantunen *et al.*, 2018; Díaz-Reza *et al.*, 2020). Several researchers have examined "remoteness" from different perspectives, discussing the benefits, design choices and implementation, such as virtual and remote labs (VRLs) (de la Torre *et al.*, 2013), virtual production systems (Dobrescu *et al.*, 2019) and virtual factory (Jain *et al.*, 2017).

However, despite the enormous potential and current availability, the integration of AMT still requires considerable human involvement on the shop floor. This fact makes the integration of AMT a time-consuming and costly endeavor impacting production performance. Studies demonstrating actual production setup, considering both operational technologies (OT) and information technologies (IT) and their interface integration, are lacking, meaning the literature provides practitioners little guidance on remote integration processes for AMT. Most publications offer low generalizability and focus on either technology or organizational aspects of the integration but lack a comprehensive and integrated framework covering both. Further, processes for creating plug-and-produce systems or architecture (Bennulf *et al.*, 2019; Eymüller *et al.*, 2021; Scrimieri *et al.*, 2021) have been developed to integrate AMT, but not for remote integration. Finally, the ability to constantly change and adjust the production system to new requirements without impacting production performance is likely to be of even greater importance in the future to ensure an efficient production process. Therefore, this paper aims to examine the remote integration process of AMT into the production system and identify key challenges and mitigation actions for smoother integration. The research is guided by two research questions.

RQ1. What are the key challenges in the remote integration process of advanced manufacturing technologies and how do companies mitigate these challenges?

RQ2. How can companies apply and realize the remote integration process of advanced manufacturing technologies into their production systems?

The study adopts a case study approach to examine the integration of Robotino (a mobile robot), as an AMT at an industrial technology center, into a cyber-physical factory. The paper presents the AMT's remote integration process by applying the plug-and-produce concept and draws on the technology–organization–environment (TOE) theory to systematically categorize the key challenges and possible mitigating actions. Finally, the paper proposes an integrated framework to support companies in realizing the remote integration process of AMTs into the production system.

2. Theoretical framework

2.1 Integrating advanced manufacturing technologies into production systems

The literature defines and categorizes AMT in different ways (Goyal and Grover, 2012; Abd Rahman and Bennett, 2009). Goyal and Grover (2012) reviewed different AMT definitions and classifications and found that a common denominator is that the technology contains both software and hardware. Today, nearly all production equipment incorporates some electronic elements, thereby fitting the definitions of AMT (Goyal and Grover, 2012). AMTs are currently associated with Industry 4.0 technologies. For instance, Sirkin *et al.* (2015) emphasized five technological tools—autonomous robots, integrated computational materials engineering, digital manufacturing, industrial Internet and flexible automation and additive manufacturing—indicating that AMTs are a set of highly flexible, data-enabled and cost-efficient manufacturing processes.

Developing and integrating AMT into production systems can create new possibilities that might also cause changes throughout the production chain (Pisano, 1997), affecting both product and production system design and contributing to long-term production system development as well as significant productivity improvements in daily production (Bellgran and Säfsten, 2010; Díaz-Reza *et al.*, 2020). Developing new AMTs also offers an immense potential to improve product quality while reducing manufacturing time, thereby leading to decreased product prices and increased profits (Díaz-Reza *et al.*, 2020). However, AMT adoption also causes several challenges. For example, Stornelli *et al.* (2021) mapped five barriers to AMT adoption in three key stages of the AMT adoption process (i.e. evaluation, setup and installation and post-installation). The barriers are economical, organizational, personnel-related, technology, policy and regulation barriers.

Integrating new AMT into the production system often stems from developing new products. Accordingly, the main reason for changing a production system is new product development, thereby triggering AMT investment and integration (Bellgran and Säfsten, 2010; Eynaud *et al.*, 2021). From a production perspective, typical requirements are tolerances, technical specifications and production volume. A suitable production flow requires considering the layout, degree of automation and AMT. When applying the plug-and-produce concept, requirements specifically related to interoperability need to be considered. Different experts (e.g. computer specialists) must collaborate with production and system engineers at detailed levels (Onori *et al.*, 2012). In the digitalization and Industry 4.0 context, future production systems must be plug-and-produce in nature, but a key challenge is the lack of standards (Ye *et al.*, 2020). Hence, new requirements must be considered when designing a production system, such as modularity, easy setup and adoption of new tasks (Wojtynek *et al.*, 2019; Wang and Zhang, 2022).

2.2 Plug-and-produce concept for integrating new technologies

Inspired by computer systems' plug-and-play concept, Arai *et al.* (2000) proposed Plug-and-Produce (PnP) to integrate new components, devices and machines into production systems with minimum configuration efforts. In modern manufacturing industries, most configurations needed to integrate new technologies, machines and robots are manually developed. Manual (re)configuration can be time-consuming and error-prone, require specific competencies and fail to provide optimal solutions in terms of quality, time to market, cost, power consumption and resource utilization (Mehrabi *et al.*, 2002).

The introduction of Industry 4.0 made PnP even more attractive as it enables flexibility in production by decreasing the configuration time and effort. Industry 4.0 also provides the technologies necessary to realize PnP, such as industrial IoT, machine learning, big data and cloud computing. PnP, together with Industry 4.0, can achieve at least a 20% decrease in reconfiguration time, a 12.5% increase in resource efficiency and a 15% reduction in cost, according to the DIMOFAC project [1].

In principle, using PnP in the industry should be possible for all machines requiring (re) configuration whenever a change occurs, such as assembly-line robots, robot cells and internal logistics. When Arai *et al.* (2000) first proposed PnP, the target application domain was assembly lines in manufacturing as adding a new robot to the line requires significant effort in the re-configuration. Several PnP researchers have relied on assembly line use cases to validate their solutions (Onori *et al.*, 2012; Da Silva *et al.*, 2022).

Despite the popularity of PnP in research, it has not found its way into the industry due to the immaturity of realizing Industry 4.0 (Masood and Sonntag, 2020). Wankhede and Vinodh (2021) identified and analyzed 36 Industry 4.0 challenges in the automotive sector and found the real-time link between physical production and the digital factory to be the topmost challenge. Hence, most industry efforts are still at the demonstrator level, such as Da Silva *et al.*'s (2022) use case at Danfoss. However, some products and tools proposed by major industries are based on or support PnP. For example, ABB has integrated the PnP "Pharma 4.0" targeting the pharmaceutical industry [2], while Bosch offers an electromechanical kit for the easy integration of applications [3].

Since the PnP proposal, extensive work has focused on different aspects and related technologies. Regarding implementation, Dorofeev *et al.* (2017) proposed four phases.

(1) *Discovery phase:* This phase registers a new integrated device in the system. During registration, the device is connected to the computer network, and a program (i.e. middleware controller) initiates communication to facilitate discovery. Once this phase is complete, the new device is added to the system and able to communicate with other devices and software in the system.

(2) *Configuration phase:* During this phase, the newly integrated device declares the capabilities, functions and services (i.e. skills) it can provide. Using the production specifications and skills, a software program configures the newly added device to perform the desired production tasks. In practice, the system selects several skills within the device and sets their parameters; this configuration should be validated to guarantee the actions' correctness. This validation can be done using simulation models integrated into the production digital twin. The device skills should abstract the details of the functions and tasks that the device can perform and should be expressed in a way that the system understands.

(3) *Production phase:* This phase focuses on production processes, activities and steps, including production plan adjustment during operations. The device is configured while considering multiple predefined products, meaning production changes for known products do not require any configuration changes.

(4) *Re-configuration phase:* Re-configuration is needed if new modules and/or skills are integrated into the devices or new products are included that require changes in devices' skill configurations.

Similarly, Bedenbender *et al.* (2017) presented six phases of PnP implementation: physical connection, discovery, basic communication, capability assessment, configuration and integration. Most of these phases are already included in the four steps presented above. In PnP projects, different knowledge domains need to be integrated, which means not only combining different knowledge bases but also creating new knowledge needed for the integration to succeed. Historically, these different knowledge domains have not collaborated in projects, but recent Industry 4.0 technologies have created new opportunities for production system development.

2.3 Technology–organization–environment (TOE) theory

The TOE theory provides an excellent theoretical lens for this study as it describes how a firm's technological, organizational and environmental context affects the adoption and implementation of technological innovation (Tornatzky and Fleischer, 1990). Technological context refers to the technological characteristics and structures influencing a firm's technology adoption, organizational context denotes common organizational attributes that may facilitate or constrain such adoption, and environmental context refers to the external circumstances that may influence the adoption (Baker, 2011; Ghobakhloo *et al.*, 2022). The TOE theory has been applied in different industrial and cultural contexts (e.g. e-business, smart manufacturing, maintenance, industrial robots, supply chain) to investigate new technology adoption (Aboelmaged, 2014; Shukla and Shankar, 2022), making it appropriate for this investigation.

As this theoretical discussion demonstrates, it is necessary to investigate the significant critical dimensions or elements to enable the remote integration of AMT in a production system to support industrial companies. Specifically, an integrative framework is needed that can holistically represent the remote integration process and the required sub-steps while addressing key challenges involved in the integration process. The current study adopted PnP and TOE theory to holistically study and analyze these critical dimensions. Figure 1 presents the schematic model developed to guide the empirical investigation. The middle part of the figure captures the synchronization of critical dimensions needed for the remote integration process of AMT in the production system, including PnP phases, existing production architecture and remote integration steps. The three side parts represent the TOE dimensions influencing remote integration. The key challenges involved and actions to facilitate smoother integration are analyzed according to the TOE dimensions.

3. Methodology

3.1 Research approach

This study adopted a case study design (Eisenhardt, 1989), which is methodologically appropriate (Edmondson and McManus, 2007) for understanding and mapping activities of manufacturing technology adoption processes (related to RQ1) and exploring and identifying challenges and ways to improve them (related to RQ2) (Yin, 2009). Several earlier studies adopted this approach for mapping new technologies adopted or integrated into production systems and associated challenges (Ahlskog *et al.*, 2017; Chirumalla, 2021). The case study approach is suitable as empirical evidence, or theoretical development of designs for remote integration of AMT is limited (e.g. Edmondson and McManus, 2007; Yin, 2009). Case studies are also more suitable for exploratory research and can capture the social and organizational contexts of a phenomenon under development (Yin, 2009), such as integrating new digital technologies for production innovation, as well as facilitating an in-depth understanding of the underlying processes or factors influencing such adoption (Eisenhardt and Graebner, 2007). This study also followed a deductive approach as we developed the guiding framework based on the theoretical analysis, followed by selecting a practical scenario for empirical observation and confirmation (Azungah, 2018).

3.2 Research setting

This work considers the Festo cyber-physical factory at an industrial technical center to explore the requirements and challenges of remote integration of mobile robots in production systems. This academic demonstrator setup is very close to the industrial setting, with continuous input from industrial partners. The purpose is to remotely integrate a mobile robot, called Robotino, into the production system. This integration is analyzed using the PnP concept by following the guiding framework (shown in Figure 1) as a starting point. The TOE theory is used to analyze and categorize the identified key challenges and proposals for mitigation actions. Finally, the analysis leads to the development of an integrated framework for the remote integration process of AMT in production systems.

3.3 Research case description

The production system used herein is a modular smart factory system for teaching and research purposes [4] (de la Torre *et al.*, 2013; Madsen and Møller, 2017) that has been used in several works to demonstrate the applicability of proposed algorithms (e.g. Andersen *et al.*, 2017; Buhl *et al.*, 2019; Um *et al.*, 2022). Its two separate islands are connected via Robotino (see Figure 2). The first island involves three stations that perform automatic storage and retrieval, check the product orientation and mount workpieces using an industrial robot. The other island involves seven stations that perform the assembly and delivery of the mobile phone. The product moves between stations on each island using smart conveyor belts and between islands using Robotino.

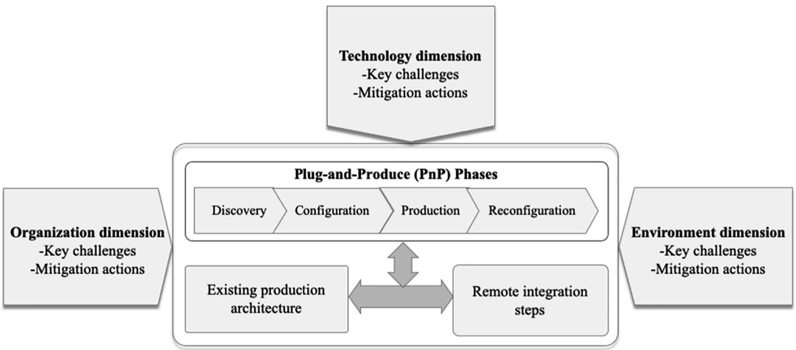


Figure 1.
Guiding integrated framework to examine the remote integration process of AMT in production systems using the PnP concept and the TOE theory

Figure 2.
Cyber-physical factory (the lab setup)

To control the factory, each station includes a controller connected to the automation network. A manufacturing execution system (MES) is integrated into the CPF intranet that communicates with the stations to commit the production orders and monitor their status. To monitor the stations' status, different sensors are installed at each station. For example, the conveyor belt has six capacitive sensors to detect every passing carrier, RFID readers and IR sensors at every station to assess the state of the order and its carrier, power consumption sensors for each island and process-specific sensors (e.g. temperature sensor, camera). Except for the bridging stations, each station includes a human-machine interface (HMI) for real-time monitoring, control and configuration capabilities that are controlled via a programmable logic controller (PLC).

3.3.1 Manufacturing execution system (MES). The MES in the CPF, called MES4, is a flexible system that can be adapted to any configuration of production stations and issue relevant commands to each station to produce the requested parts (Ružarovský *et al.*, 2021). At the heart of MES4 are the work plans that define a set of steps to be performed to construct a specific product. These steps are described in terms of actions on production cells also stored within the MES4. MES4 contains information about each ordered product and which parts of the relevant work plan have been completed for that specific product. Such a level of detail means MES4 can successfully route subproducts between different production islands when the next step to be performed can only be completed on another production island.

3.3.2 Production process. The production process begins at the automatic storage and retrieval station, where the base cover of the product (mobile phone) is placed on an empty carrier; the carrier then holds the order number (programmed on its RFID tag) and passes through the measurement station to verify the base cover orientation. If the orientation is correct, the carrier moves to the robotic assembly station to place the printed circuit board (PCB) with one or two fuses according to the production order. Next, the mobile robot (Robotino) moves the carrier to the other island, where the visual inspection station verifies that the correct PCB and fuses are mounted; the drill station makes the required holes, the magazine station places the correct cover according to the production order, the press station presses the cover, and the label station adds the label. Finally, the delivery station delivers the mobile phone. The carrier is sent back to the automatic storage station using Robotino.

At each station, progress is verified by reading the RFID and deciding whether to continue producing the product. As the production units are technically independent, the CPF supports the simultaneous production of several production orders.

4. Results

This section first presents the AMT's remote integration PnP process using Robotino (mobile robot) and then describes the key challenges encountered and actions to overcome the challenges using TOE theory. The section concludes with an integrated framework for the remote integration process of AMTs into the production system using the PnP concept and the TOE theory.

4.1 Integration of robotino into the cyber-physical factory

Robotino is an automated guided vehicle (AGV) equipped with multiple sensors and cameras to enable it to move independently and provide material transport. It is supported by software components that provide services to control the robot. These services can be accessed from a web interface using a dedicated protocol. As MES4 uses a different protocol to communicate with the production stations, to integrate Robotino with the CPF, dedicated software was developed called Festo Fleet Manager to bridge these two protocols. Figure 3 illustrates this integration process, which involves two steps performed by two engineers.

(1) Commission step to install Robotino and FM.

(2) Integration step to integrate Robotino into MES.

The commissioning step requires physical work on the shop floor to unpack Robotino and connect it to the network. It also involves installing the fleet manager (FM) software and ensuring that Robotino is controlled from FM. As this paper focuses on integrating AMTs into production systems, the integration of Robotino into CPF is detailed in the following section.

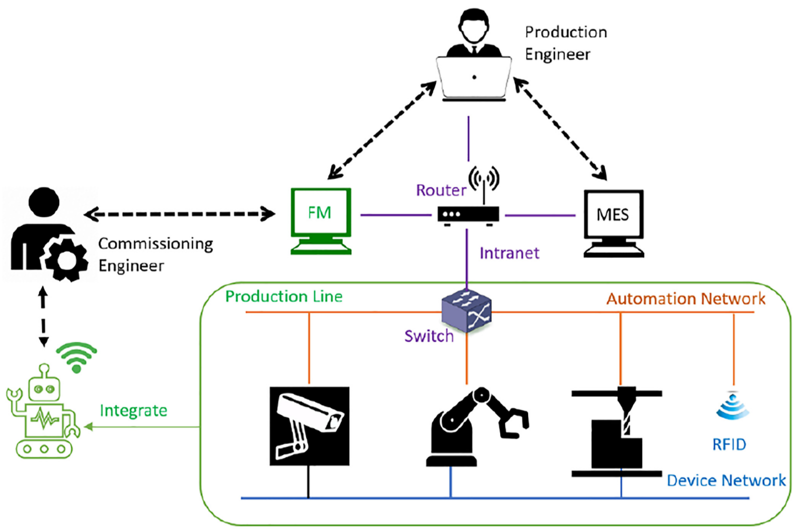


Figure 3.
Robotino (AMT) integration process with CPF

4.1.1 Steps for integrating robotino into MES and FM. The following steps integrate Robotino and the related resources into the MES and FM.

(1) Define the resources, and their MES IDs used to deliver or pick up a product from Robotino according to the production process.

(2) Add Robotino to MES as a new resource (see Figure 4a).

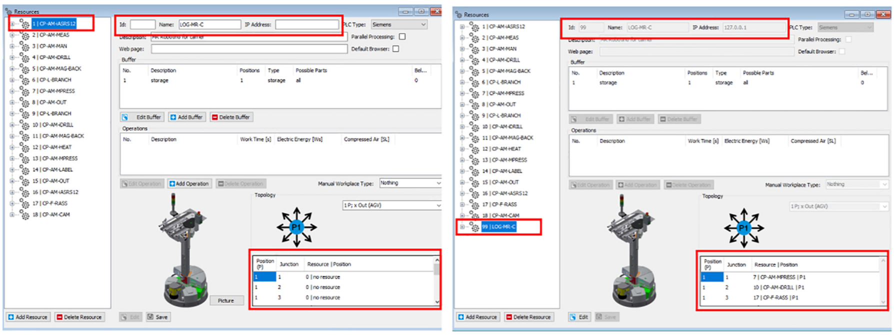
(3) Configure Robotino according to information from Step 1 (see Figure 4b).

(4) Update the configuration of the resources using Robotino according to the information from Step 1 (Figure 5).

Once Robotino and related resources are configured in MES, they can be added to FM using the following steps (see Figure 6).

(1) Teach Robotino the position of each resource that will collaborate with it as defined in Step 1 and give it a Position ID. This step is done manually using a dedicated software system called Robotino Factory.

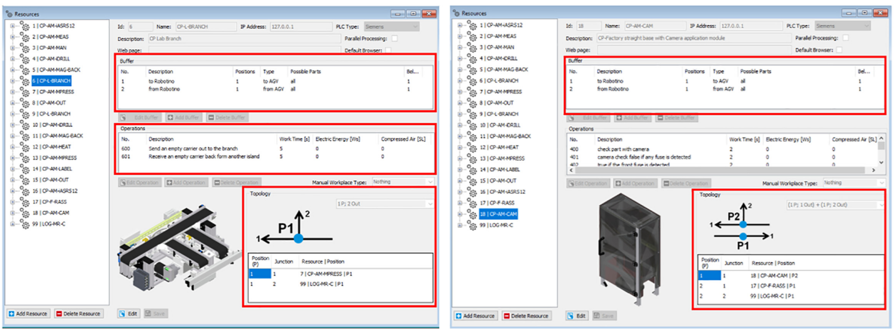
(2) Run FM and find the Robotino IDs connected to FM (Figure 7). When FM starts, it automatically detects and lists all connected Robotino IDs in the Fleet Commander Center.



Adding Robotino
(a)

Configuring Robotino
(b)

Figure 4.
Adding and configuring Robotino in MES



Branch unit
(a)

Camera unit
(b)

Figure 5.
Updating the configuration of related resources in MES

(3) Add the Robotino ID (from Step 6) and its MES ID (from Step 3) to the list of Robotino (Figure 6a).

(4) Add the Position ID (from Step 5) and the MES ID (from Step 1) to the Position List (Figure 6b).

(5) Add the MES IP address and port number to the MES System Information.

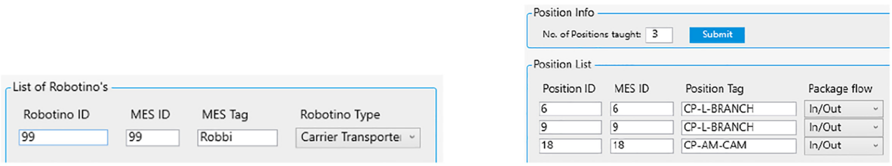
Once the integration process is completed, it can be tested by assigning a task to Robotino from MES and monitoring the messages between MES and Robotino via FM (see Figure 8).

Based on the PnP phases explained in Section 2.2, the integration steps can be mapped to the PnP phases as shown in Table 1.

4.2 Remote integration process of robotino

This subsection presents a design process for integrating Robotino in CPF using a remote integration web service; it is based on the analysis results from the previous subsection.

4.2.1 PnP as a RESTful web service for remote integration. The RESTful web service design [5] is used to improve the integration process agility and flexibility. Figure 9 shows the proposed architecture.



Robotino information
(a)

Position information
(b)

Figure 6.
Adding information to FM

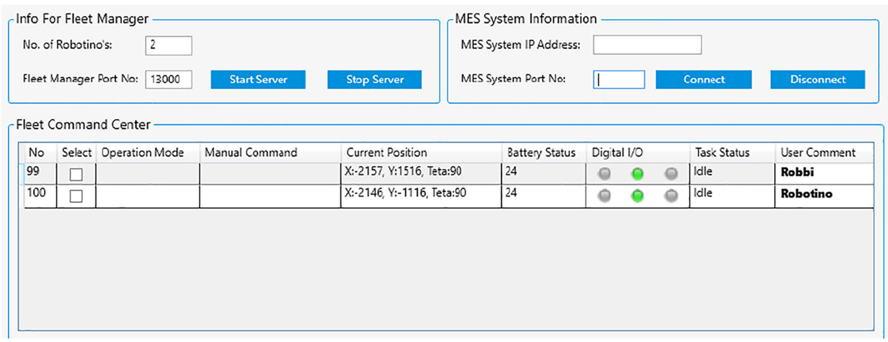
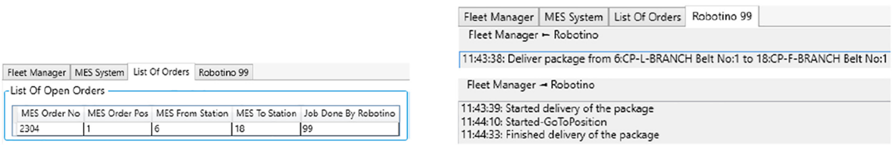


Figure 7.
Connecting robots to FM



Messages from MES to FM
(a)

Messages between FM and Robotino
(b)

Figure 8.
Messages between robotino and MES via FM

Web services are platform-independent, low-coupling, self-contained, programmable web-based applications that can be described, published, discovered, and coordinated using an open extensible markup language (XML). Applications implemented according to the web service specifications can exchange data with each other regardless of languages, platforms, or internal protocols used. Therefore, web services provide a common mechanism for integrating business processes between the entire enterprise and even multiple organizations (Zhou *et al.*, 2021). RESTful is a software architecture based on resource-oriented architecture (ROA) developed to manage IoT applications (Lee *et al.*, 2014). RESTful web services are characterized by their addressability, connectedness, homogenous interface and statelessness, allowing self-configurability, interoperability, scalability and reliability (Lee *et al.*, 2014).

PnP phase	Integration step	Explanation
Discovery phase	1, 5, 6	Gets information from the production process and installed Robotino software
Configuration phase	2, 3, 7, 8, 9	Adds information related to resources in the production process and to Robotino
Production phase	4, 9	Adds information related to MES and the production process
Re-configuration phase	4, 5	Updates information according to a new production process

Table 1.
Mapping integration steps to PnP phases

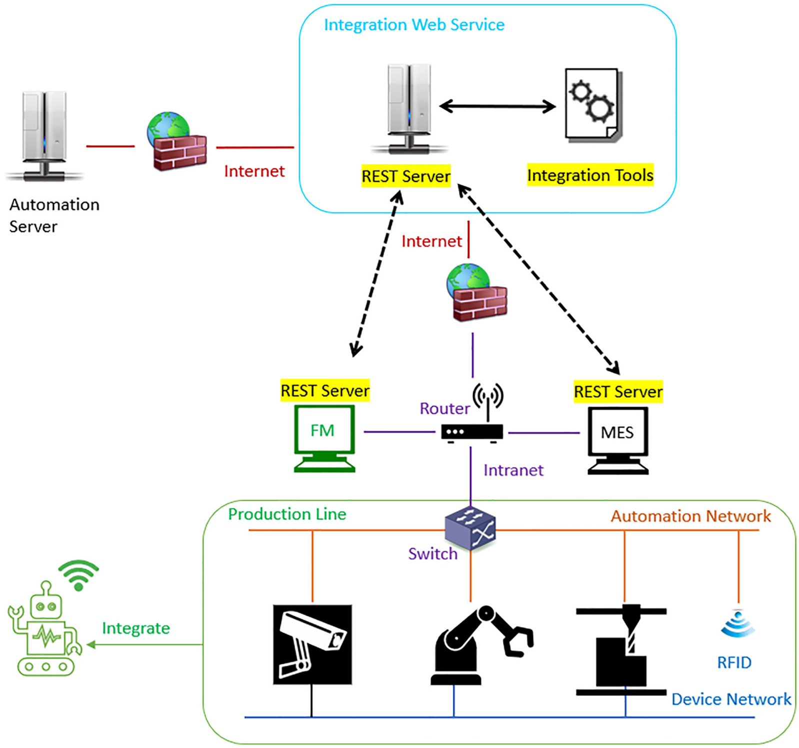


Figure 9.
Remote integration process as a RESTful web service

(1) Addressability: all resources can be accessed using uniform resource identifiers (URIs).

(2) Connectedness: resources must be linked with related resources to be presented to servers or users.

(3) Homogenous interface: all resources are used by the basic four Hypertext Transfer Protocol (HTTP) methods (i.e. get, put, post, delete).

(4) Statelessness: connections made between servers and clients do not create sessions; therefore, servers do not store the client state and clients must express their current state via HTTP header and body.

4.2.2 MES as a RESTful web service. MES is a database containing information related to the production system's available resources, working plans and production orders (Brunoe *et al.*, 2019). A RESTful API is developed to interact with the MES database. The API has several commands that permit reading and writing different values in the database that start with "get" and "set." For example, the command "getResources" will return all resources available on the production system with their statuses; the command "setNewOrder" will start a new production order with a user-defined order number.

4.2.3 FM as a RESTful web service. Like MES, FM is a database containing information related to available mobile robots, working positions and connected MES (RobotinoWiki contributors, 2019). A RESTful API is developed to interact with FM. The API includes several commands that permit reading and writing different values in the database starting with "get" and "set." For example, "getPositions" will return all positions that the robot can use to pick up or deliver a product while "setRobot" will add a robot to the list of robots with user-defined arguments.

4.2.4 Integration tool as a RESTful web service. An API was developed for the integration tool that permits an external user to submit an integrated command and get back the integration status. The command "integrate" initiates a series of commands based on user-defined arguments to integrate Robotino into CPF and returns the integration status (see Figure 10).

4.2.5 Remote integration process. The integration tool was designed using the PnP concept explained in Section 2.2 (Figure 10). In the discovery phase, the tool requests the MES and FM resource structures using user-provided arguments (mesIP and fmIP). These structures enable the tool to parse the resources and find those related to the integration process using user-provided arguments (robotinoID and servingPoints). The (re)configuration phase adds and configures Robotino and related information in FM. In the production phase, Robotino and related resources in the CPF are added, configured, or reconfigured. The last phase is to verify the integration state and return its status to the user, who could be an engineer who initiates the remote integration process or an automation server that initiates the integration process automatically based on the need for new production resources. It is worth noting that the integration phases are mutually exclusive while some processes inside each phase can be overlapped.

4.3 Key challenges and mitigation actions: TOE dimensions

This section presents the challenges (C) and mitigation actions (MA) according to TOE dimensions. For example, T-C1 indicates technology challenge number one.

4.3.1 Technology (T) dimension. 4.3.1.1 T-C1 – AMT selection. The fast advancement and variability of AMTs make the selection of the appropriate AMT and the time of integration challenges.

4.3.1.2 T-MA1 – technology roadmap and proof of concept. One way to facilitate the selection of the appropriate AMT and the time of integration is to use a technology roadmap

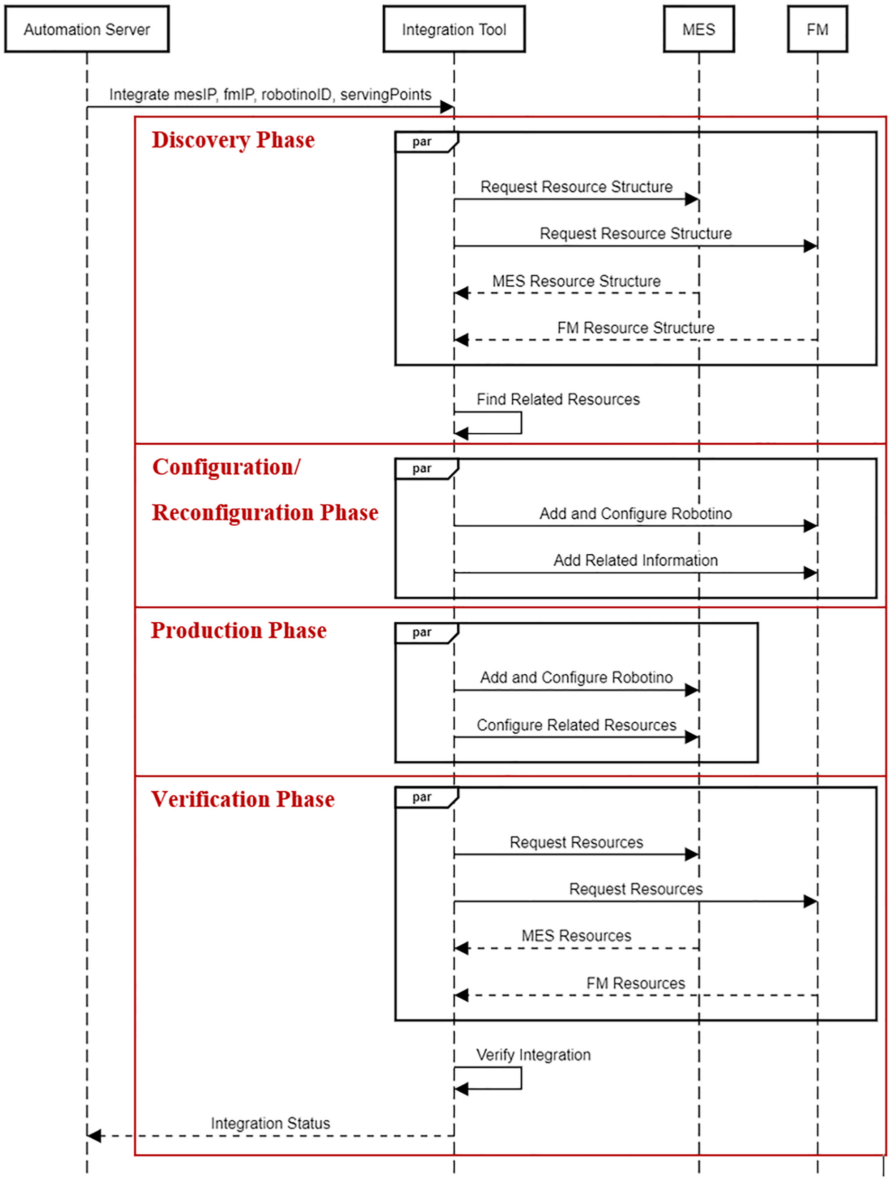


Figure 10.
The remote integration process of mobile robots in a production system

and provide proof-of-concept tests, using digital twins for example, before integrating technologies into the production system.

4.3.1.3 T-C2 – AMT requirements. Some AMTs need manual calibration before being integrated into the production system. In our case study, for example, the current Robotino integration process requires manual learning of serving points in the operational space. Once the integration process is completed, the mobile robot must learn the position of the serving points and the paths between these points.

4.3.1.4 T-MA2 – automatic calibration. Select an AMT that can be calibrated automatically. In our case study, for example, a more advanced mobile robot could be used with advanced sensors and software that enable it to automatically navigate between serving points without the need for manually learning these serving points and paths between them.

4.3.1.5 T-C3 – closed software. Most production system software (e.g. MES and FM) are closed systems developed without any possibility of adding new functionalities or interacting with other systems. However, the proposed remote integration process presents a need to add new interfaces to MES and FM to enable querying and updating of resources' configuration remotely.

4.3.1.6 T-MA3 – software adaptation. One solution could be providing open-source versions of production system software with very good documentation to be able to make changes. However, making changes to such big systems could be challenging even for experienced programmers, and modified software could face the potential loss of certification and significantly more difficult version upgrades. Furthermore, some software providers might not be inclined to reveal their software code due to industrial secrets. Other solutions could be redesigning these systems in a more modular way and providing them as modular software services, such as currently popular microservices architecture (Bigheti *et al.*, 2019), that can be easily integrated with other software services. We believe that the second solution is more suitable for the remote integration of AMTs in cyber-physical production systems.

4.3.1.7 T-C4 – different data structures. Different software in the production system (e.g. FM and MES) use different data structures, making it challenging to identify the needed resources in the integration process.

4.3.1.8 T-MA4 – common information model. A common information model can be built for the storage and exchange of production system information. Standards for information representation and exchange, such as AutomationML and ISA-95 standards, should be used.

4.3.2 Organization (O) dimension. 4.3.2.1 O-C1 – lack of knowledge. When applying the PnP concept and remote integration of Robotino, different types of knowledge domains are needed during the integration process. Traditional production engineering knowledge is not enough for this integration work. PnP and the development of a smart factory require input from a range of knowledge domains (e.g. IT/OT knowledge, production knowledge).

4.3.2.2 O-MA1 – combining different knowledge domains. Although these knowledge domains may exist within a company, they often have not previously collaborated. Therefore, cross-functional teams constituting these knowledge domains should be arranged. When integrating the Robotino knowledge, the commissioning and production engineer should be combined through cross-functional work.

4.3.2.3 O-MA2 – external knowledge (if necessary). Knowledge domains are missing within the organization, one solution is to involve an external partner in the remote integration process, although companies then become dependent on an external partner. Another solution is to define and develop a new role within the organization and recruit a person with the necessary knowledge. Determining how to proceed requires a strategic decision.

4.3.2.4 O-C2 – lack of role description. Without previous knowledge about PnP and the remote integration of AMT into production systems, an industrial challenge is defining the new role description. What type of knowledge is necessary for enabling remote integration?

4.3.2.5 O-MA3 – specifying new role description. When specifying the role description, input from various organizational functions should be included, and responsibilities, ways of working and organizational collaboration interfaces should be defined.

4.3.2.6 O-C3 – increased complexity. The purpose of using PnP is to automate, although it also increases complexity in the production system. The remote integration of Robotino includes both SW and system adjustments; therefore, organizational knowledge needs to be developed.

4.3.2.7 O-MA4 – organizational training. Based on the degree of newness of the technology integrated into the production system, education and training programs need to be arranged at various organizational levels. A high degree of newness might require involvement or collaboration with external partners.

4.3.2.8 O-C4 – old way of working. Remotely integrating Robotino or other AMT into a production system creates a new way of working. The integration process and required steps are dependent on the legacy system—in this case, the FESTO equipment.

4.3.2.9 O-MA5 – new way of working and standardization. Manufacturing companies need to standardize and specify the low-level architecture and how to communicate with higher levels. An overall system architecture should be developed and standardized, which can be problematic due to the legacy system and knowing where to start. Remote integration should also be performed by trained staff who know how to perform the PnP properly.

4.3.3 Environment (E) dimension. 4.3.3.1 E-C1 – interoperability. Like most production systems, FESTO CPS uses custom communication protocols in various parts of the system, making the integration of new manufacturing technologies that do not use similar protocols challenging.

4.3.3.2 E-MA1 – unified communication interface. Open Platform Communication with uniform architecture (OPC-UA) has been presented as a standard that can solve interoperability issues in communication. Although OPC-UA is supported by FESTO CPF, it should be fully integrated into all parts of the system and adopted as the primary communication protocol. In addition, an OPC-UA-associated data model that captures the system information model needs to be synchronized with the models used by the software systems (e.g. MES and FM).

4.3.3.3 E-C2 – security. Internet exposure in any production facility creates the potential for cyberattacks (Stellios *et al.*, 2018). In our case, the Internet connection among the integration web, automation, and MES and FL servers (see Figure 9) might be subject to attacks. By attacking a less important system exposed to the Internet, the attackers can gain access to and compromise higher-value targets. This is particularly dangerous in production systems as cyberattacks can easily translate to physical harm or mechanical damage.

4.3.3.4 E-MA2 – secure and authenticated communication. Different systems should always communicate over secure and authenticated channels when moving data across the Internet. One standard approach to securing communications is using virtual private networks (VPNs) that create a secure and private network as a layer on top of the traditional Internet infrastructure.

4.3.3.5 E-C3 – new types of requirements. Historically, when integrating AMT in production systems, requirements like product tolerances, technical specifications and production volume have been considered and, consequently, suitable production flow, layout and degree of automation have been investigated. PnP also requires the consideration of new types of requirements, like modularity, easy setup and adoption of new tasks.

4.3.3.6 E-MA3 – redefined requirement specifications. To enable PnP and the creation of a smart factory, manufacturing companies need to rethink the requirement set in the AMT requirements specification. Requirements in the form of quality measures change over time, and cycle time is not enough given the recent trends of smart manufacturing and PnP. Sensors/actuators, communication technologies, and protocols should also be defined in requirement specifications to enable PnP possibilities and remote integration.

Based on the results of the remote integration process of AMT using PnP, as well as the key challenges and mitigating actions identified using the TOE theory, this study developed an integrated framework for the remote integration of AMT into the production system (see Figure 11). The integrated framework includes details of the guiding framework (Figure 1 in

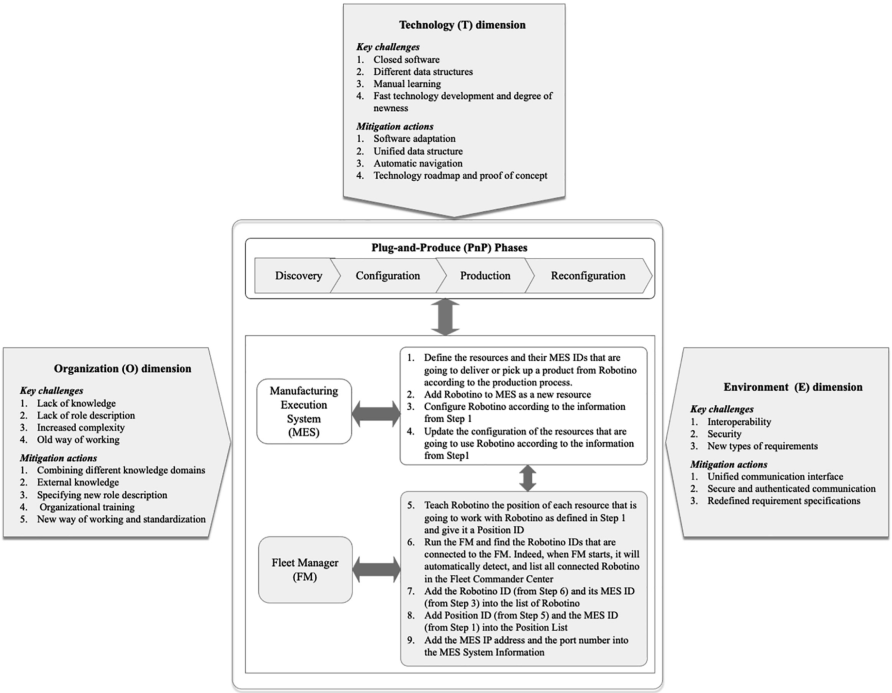


Figure 11. The proposed integrated framework for the remote integration process of AMTs into the production system by using the PnP concept and the TOE theory

Section 2), PnP phases and required remote integration steps (Sections 4.1 and 4.2), and key challenges and mitigating actions to facilitate a smoother integration process (Section 4.3). The proposed integrated framework indicates key aspects of remote integration to be considered along the dimensions of Technology, Organization and the Environment, describing how PnP four phases could be used to achieve the required remote integration in 9 steps in relation to the Manufacturing Execution System (MES) and Fleet Manager (FM). To implement the remote integration of AMT, companies can first use the proposed integrated framework to assess and reflect on key challenges involved in the remote integration of AMT among the PnP phases such as discovery, configuration, production and reconfiguration. Secondly, companies can use the proposed mitigating actions to overcome the context-specific challenges among the PnP phases to achieve a smoother remote integration by following the proposed nine steps. Finally, with a structured approach, the proposed integrated framework would facilitate OT and IT integration by involving relevant people or resources from different organizational functions. Specifically, the framework would enable a holistic perspective and enhances the cross-functional collaboration in smart factory teams to reduce dilemmas in early decision-making.

5. Discussion and conclusion

Despite the positive potential of remote integration of AMT for enabling smart production scenarios, knowledge about the process from considering both technological and organizational issues have been scarce. Our research has helped to close the knowledge gap by examining the remote integration process of AMT (i.e. mobile robots) into the production system by detailing the proof of concept and identifying key challenges and mitigation actions for a smoother integration.

Guided by two research questions (RQ1 and RQ2), this study identified the TOE and PnP theories as a promising approach. In line with the TOE framework, our study contributes to the remote integration debate by showing that the ability for remote integration of AMT is affected by technological, organizational and environmental issues. For effective remote integration of AMT to take place, it seems necessary to have a holistic perspective and ensure that certain production domain competencies, both in terms of understanding the constraints of the current production set-up and in terms of understanding the impact of the new technology. To address the first RQ1, a total of eleven key challenges and twelve mitigation actions were identified clustering them into either technological, organizational, or environmental challenges. The answer to the first research question contributes to achieving the objective by increasing the understanding of the challenges encountered in the remote integration process of AMT and how the challenges can be mitigated. Answering the second RQ2 involved identifying a framework supporting manufacturing companies with a process for remote integration of AMT considering the existing production architecture. The answer to the second research question contributes to achieving the objective by increasing the understanding of how the process can be applied and shaped to best fit the specific context of where the technology needs to be integrated.

The answers to the two research questions were synthesized into an integrated framework, see Figure 11. The purpose of developing the integration framework is to create a valuable tool that can be applied to effectively manage the remote integration of AMT. The challenge for manufacturing companies is to acknowledge that remote integration requires multiple competencies and advanced preparation in the organization. i.e. multiple activities need to be performed to be successful. The various activities that need to be conducted make it impossible to manage the remote integration process just from a technological perspective. As the integration process of AMT is critical to production performance, our study deepens the understanding of remote integration in a previously unexplored context. These findings are particularly interesting considering the desire of managers and academics to find new ways to enable constant adoption of the production system to new requirements in an efficient way with a short time to volume and high production efficiency from production start.

The costs and benefits of the proposed framework can be analyzed by comparing Figures 3 and 9, where Figure 3 represents the conventional AMT integration approach while Figure 9 represents the proposed remote integration approach. The cost of the conventional integration process includes downtime loss, AMT cost, commissioning cost and expert cost. The remote integration also includes all these costs except the expert cost. However, downtime loss can be minimized, and the commissioning cost can be reduced by proper scheduling and automation of the integration process. The greatest benefits are flexibility, less downtime and the effectiveness of the integration process.

5.1 Theoretical and managerial implications

Our study offers important implications for research related to AMT management (e.g. Chaoji and Martinsuo, 2019; Stornelli *et al.*, 2021) as well as reconfigurable and virtual manufacturing systems (e.g. Rösiö and Bruch, 2018; Dobrescu *et al.*, 2019). First, the study offers new insights into AMT management. We present an integrated framework for the remote integration of AMT into the production system by applying PnP and TOE theory. The findings thus extend previous research related to remote access and the integration of AMT (e.g. Liu *et al.*, 2020; Jantunen *et al.*, 2018) as well as the process view of integrating AMT (e.g. Rösiö and Bruch, 2018; Stornelli *et al.*, 2021) by addressing in detail the activities required for remote integration of AMT. These findings are important because existing processes lack sufficient details of what needs to happen at different levels and what challenges need to be dealt with. By presenting this descriptive framework, a critical step is taken to increase knowledge for enabling efficient remote integration processes.

Further, our study deepens the understanding of key challenges encountered in the remote integration of AMT and mitigation actions to overcome the challenges. While some of the challenges and possible mitigation actions have been reported previously that our research is one of the first that combines both organizational and technical issues critical for remote integration. Consistently with the TOE theory, our findings suggest that there is a need to consider the challenges and mitigation effects from various levels inside and outside of the factory. To our knowledge, none of the research presented previously has applied the TOE perspective to the remote integration of AMT. Accordingly, in contrast to previous research, we provide a more comprehensive and detailed view of challenges and mitigation tactics compared to the general levels discussed in existing literature (Stornelli *et al.*, 2021). Although the research has focused on the integration of a mobile robot, the challenges and mitigation activities discussed are also of relevance for integrating different AMTs in production systems (e.g. Chaoji and Martinsuo, 2019; Chirumalla, 2021; Liu *et al.*, 2020; Jantunen *et al.*, 2018; Stornelli *et al.*, 2021).

Third, this study contributes to the discussion of using PnP in designing and integrating AMT into production systems (Bennulf *et al.*, 2019; Eymüller *et al.*, 2021). Although some of the previous research (e.g. Bedenbender *et al.*, 2017) applies a similar approach, i.e. using a bottom-up approach starting from a use case to determine how existing solutions might fit. However, in contrast to our work, they considered field devices whereas we focused on AMT in manufacturing that needs to be integrated with different types of production systems. In addition, the use cases considered in previous research have been rather general not building on a real production system in line with the use case applied in our research. Furthermore, we combined remote integration with PnP and included not only technical aspects but also organizational and environmental aspects (TOE) in an integrated manner. To the best of our knowledge, no previous work has covered these aspects of PnP. Thus, our work can be seen as complementary to the current state-of-the-art works focusing mainly on the application and integration of PnP in existing production systems (i.e. MES, FL).

Fourth, the paper contributes to the discussion of the importance of OT and IT integration and the involvement of relevant people or resources or knowledge domains in the Industry 4.0/smart factory implementation (e.g. Chirumalla, 2021; Sjödin *et al.*, 2018). In particular, it contributes to literature emphasizing the importance of people, processes and technology as key dimensions for Industry 4.0 implementation (e.g. Sjödin *et al.*, 2018). Previous research has focused on technical aspects (IT/OT) whereas this research combines technical aspects with softer organizational and environmental aspects, such as knowledge development, way of working and new requirement specifications. By combining these three aspects into a real-time problem, the study proposed both mitigated actions and a framework.

Finally, this study's findings are useful for production managers, automation engineers, IT engineers and managers and process development leaders seeking to learn more about the remote integration of new AMTs into the production system. Above all, our findings clarify which activities need to be addressed to facilitate the remote integration of AMT holistically. Following the framework proposed, our findings imply a call for a formalized process considering both technical and organizational issues inside and outside of the organization. On this basis, the framework may reduce uncertainty among project members and will most likely decrease the time required to configure new AMT into production systems.

Moreover, beyond the importance of following a structured process cross-functional collaboration between IT and OT as well as with technology providers is important to enable remote integration and increase speed for integrating AMT. The involvement of different functions and backgrounds will help to identify critical issues required to be dealt with before the start of production. Accordingly, managers need to pay attention that domain knowledge is integrated early in the process and cross-functional activities will take place.

Furthermore, the analysis of challenges and mitigation actions using the TOE theory provides a good starting point for practitioners in the early stages of remote integration, helping them understand how their firms' contextual factors affect AMT integration and implementation, which could improve subsequent project phases. With fewer efforts required to configure new AMTs into the production systems, industrial practitioners can continue production while integrating new AMTs, thereby avoiding downtime while improving flexibility. The key challenges and mitigation actions discussed in the frame of the TOE dimensions, which are based purely on a practical perspective, help develop a comprehensive view and improve the cross-functional understanding of the AMT integration process. Specifically, the results can support smart factory teams and reduce dilemmas in early decision-making. Finally, this study emphasized the significance of different cross-functional knowledge domains and discussed the kinds of expertise companies need to ensure the successful remote integration of AMTs. Thus, the proposed framework can already be deployed by industry professionals in their efforts to integrate new technologies with shorter time to volume and increased quality but also as a means for training employees in critical competencies required for remote integration.

5.2 Limitations and future research

Due to the complexity of integrating new machines in general and using remote integration with PnP, this study mainly focused on the integration phase and did not cover the pre-integration phase (i.e. preparation and operation phase), which requires continuous monitoring of the production processes and adaptation of the configuration. The study only considered adding one robot; the complexity increases when multiple robots with different capabilities are required. Determining how to assign tasks to these robots dynamically is an important direction for future research. Moreover, our findings are based on a specific robot and production system, which are commonly used in many applications and similar to many other industrial robots and production systems; however, our results can be generalized to any AMT that provides the same integration capabilities (interfaces and integration functionalities) as Robotino.

The study is based on an academic demonstrator setup at an industrial technical center, which might cause a few limitations when analyzing key challenges and mitigation actions according to the TOE dimensions. For example, we did not consider certain dimensions, such as slack and size, industry characteristics and market structure and government regulations, which offers possibilities for future work to evaluate the framework in a real-time industrial case. When it comes to people and organizations, more groups from the factory (from the supply chain) should be considered in future investigations, such as maintenance engineers who should be involved. Although the potential of the proposed framework is evident from the case study, future work should consider and evaluate the benefits of the framework in production environments in terms of quality, cost, delivery and flexibility, in particular, a cost-benefit analysis. Moreover, the framework can be used to define different propositions/assumptions related to the remote integration process, which can be tested and assessed using real industrial cases.

The presented solutions can be seen as a first step in developing a digital twin (DT) that will be responsible for PnP and remote integration. The DT should also be able to support virtual commissioning to allow integration to be evaluated even before the real machine and/or robot is integrated. Building such a DT is part of our ongoing work.

Notes

1. https://dimofac.eu/2021/02/26/how-plug-and-produce-technology-will-automate-production-line-reconfiguration-in-dimofac/
2. https://new.abb.com/news/detail/54532/abb-and-werum-it-solutions-collaborate-on-next-level-plug-and-produce-solution-for-pharma-40
3. https://www.boschrexroth.com/en/xc/company/press/index2-36288
4. https://www.festo.com/us/en/e/technical-education/learning-systems/factory-automation-and-industry-4-0/learning-factories/cp-systems-large-scale-industry-4-0-learning-factories/cp-factory-id_36140/
5. REST – Representational State Transfer.

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