Journal of Computer Science

Research Article

Methodology of the Development of Production Digital Twins Using a Simulation Experiment

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Article history
Received: 07-01-2025
Revised: 08-03-2025
Accepted: 10-05-2025

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Abstract: The simulation experiment evaluates whether the business process model accurately replicates real-world operations and whether the digital twin functions in real-time. A digital twin of a production business process is a virtual representation of its real-world counterpart. Its aim is to monitor the execution of the actual production business process in order to detect irregularities and production downtimes early and respond promptly by making optimal decisions. This paper presents the position of digital twins of business processes in relation to business process documentation, business process simulations, and the execution of process-oriented applications. The research problem is that existing business process management methodologies are not designed for the development of digital twins of business processes, and there is no established methodology that outlines the process of creating a digital twin of a production business process. The aim of this research paper is to introduce a methodology for developing production digital twins using the simulation experiment method. The significance of the proposed methodology lies in overcoming the limitations of current business process management approaches, which lack adequate support for developing digital twins. Therefore, it is important to enhance existing business process management methodologies to align them with modern requirements, particularly in the rapidly evolving domain of Smart Industry. To validate the proposed methodology, a digital twin model was developed for a private, non-profit organization operating a smart factory that produces drones. The results of the comparison between the simulated model and the production digital twin show no deviations in process duration between these two models. Additionally, the digital twin of the production business process accurately reflects its real-world counterpart in real time.

Keywords: Digital Twin, Simulation Experiment, BPM, Camunda

Introduction

With the rapid progress of computer and communication technology, virtual simulation experiments based on the digital twin are becoming increasingly sophisticated. According to Križanić and Vrček (2023) digital twin of a business process represents a virtual replica that mirrors the behavior and structure of the actual business process. The resilient real-time optimization framework relies on digital replicas of business processes and integrates both physical and virtual environments. One of the key benefits of employing digital twin technology is its ability to support the real-time optimization of business processes. The digital twin is capable of accessing relevant parameter data in real time and subsequently adjusting the simulation dynamically (Wu *et al.*, 2023). Simulation experiments play an important role in the development of digital twins as they enable the testing and validation of digital models in a controlled virtual environment. These experiments allow developers to replicate real-world conditions, simulate various operational scenarios and observe system behavior without disrupting physical processes. Through iterative simulations, developers can fine-tune the digital twin and optimize its accuracy and performance in mapping the physical entity. In addition, simulation experiments help in identifying potential issues, predicting system responses and testing "what-if" scenarios, which improves decision-making and supports real-time operational adjustments. By using advanced, real-time simulation, organizations can develop robust digital twins that can continuously learn and evolve, improving overall system efficiency and reducing risk. The

DOI: 10.3844/jcssp.2025.1379.1390

advantage of the digital twin over classic simulation is that digital twin communicates in real time with the real entity and updates its performance based on current real-time data. The simulated business process model is based on existing historical data and is not updated with current data in real time.

Creating a digital twin of a business process requires the utilization of Internet of Things (IoT) sensors and devices that supply data from the actual physical system. Beyond applications such as smart cities, smart grids and smart homes, industrial enterprises in particular stand to gain substantially from incorporating industrial IoT technologies into their operational processes. Through the transformation of analog information into digital data suitable for real-time processing, new business models can be enabled (Stoiber and Schönig, 2024).

The research problem is that existing methodologies for business process management are not geared towards the development of digital twins of business processes and that there is no methodology that explains how to develop a digital twin of a production business process. The goal of this research paper is to present the methodology of the development of production digital twins while using the simulation experiment method.

The research questions are:

1. What are the key steps involved in the methodology for developing production digital twins?
2. How can the developed methodology be used to create a digital twin of a production business process?

The contribution of this study stems from its effort to position digital twins of business processes within the structure of current business process management approaches and to highlight the necessity of expanding existing methodologies for business process management, which are currently not enough suited for the development of digital twins of production business processes. Accordingly, an additional contribution of this research is the suggestion to extend existing business process management methodologies and to propose a specific methodology for the development of digital twins of production business processes. This proposed methodology is designed to meet the requirements of Smart Industry.

The research is structured as follows: Chapter *Materials and Methods* describes the research methodology used to conduct the research in this study. *Literature review* presents the results of previous research in the field of digital twin and simulation experiment in combination. Chapter *Business process of a drone production: A case study* describes the use case of a drone production used to conduct the simulation experiment. The methodology for developing a digital twin of a production business process is presented in *Proposed methodology of the development of the production digital twins*. How a digital twin of the production business process is developed and the benefits of using digital twin technology in production business processes are presented in *Digital twin of the production business process*. The last chapter ends with a conclusion and ideas for future work.

Materials and Methods

A case study was conducted as part of the research, using the data collected from a real-world system focused on drone production. Additionally, a preliminary literature review was performed. For the purpose of this research the scientific databases Web of Science (WoS) and Scopus were searched. The keywords used for the search in the scientific databases are listed in Table (1). In addition, Table (1). presents the number of search results from which the most relevant articles for the research area were selected. The articles were selected based on search results using the keywords "digital twin" and "simulation experiment". The time span ranged from 2019-2024 in both databases, as the search focused on the most recent articles. The search in Scopus yielded 119 articles, while the search in WoS yielded 23 articles. The results in Scopus were sorted by relevance. Of the 119 results in Scopus, the first 40 articles were selected for a “quick analysis” in which the titles, keywords and abstracts of the articles were analyzed. Of the 40 articles examined, the 8 articles that best suited this research were selected for a more in-depth analysis. Some of the articles repeated in both scientific databases, Scopus and WoS.

The most relevant articles for this research were chosen from the search results, with the findings presented in the *Literature review* chapter. Studies whose results were selected are presented in the *Literature review* because they provide valuable insights into the development and optimization of digital twins using simulation experiments, which is central to the research on production digital twins.

Table 1: Strategies of the database research

Scopus Strategy of Research	No. of Articles
TITLE-ABS-KEY ("digital twin" AND "simulation experiment") AND PUBYEAR >2018 AND PUBYEAR <2025	119
WoS strategy of research	
"digital twin" and "simulation experiment" (All Fields) Publication Date: Last 5 years	23

Each article contributes to understanding how digital twins are applied in various production environments, from supply chain management to manufacturing systems and intelligent building construction. These studies demonstrate the role of simulation experiments in refining digital twin models, optimizing processes and enhancing system performance, thereby directly supporting the methodology proposed in this research.

DOI: 10.3844/jcssp.2025.1379.1390

The research methodology of this article is based on a combination of best practices for conducting software engineering research as proposed by Shaw (2003) as Švogor (2016) did in his doctoral thesis. Švogor (2016) states 3 clearly defined and reproducible phases:

1. The problem definition phase, where the research problem is identified and formulated using current scientific knowledge. The research problem of this article is that existing methodologies for business process management are not geared towards the development of digital twins of business processes and that there is no methodology that explains how to develop a digital twin of a production business process
2. The solution phase, where a solution to previously defined research questions is proposed using current insights and known principles. This article proposes a new methodology of the development of the production digital twins and its steps based on existing methodologies
3. The verification phase, where experimentation is used to verify whether the model's predictions align with the actual measurements obtained from the real-world system. In this phase, a production digital twin is developed that monitors the state of the real business process.

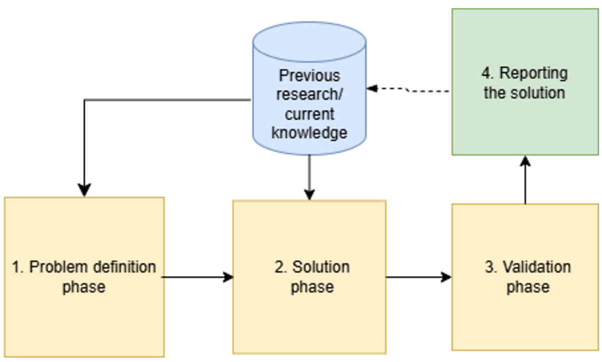

Fig. 1: The three-phase research method developed by Švogor (2016)

To create a digital twin of a real production business process, several use cases were explored. However, a private organization in Switzerland was selected, which conducts and supports industry-related and applied research and development, as the focus for this case. The organization operates a highly automated smart factory that produces drones, incorporating advanced technologies such as robots, IIoT and 3D printers. This setup serves as a good example for demonstrating the development of a digital twin in a production environment.

Literature Review

This chapter presents the results of previous research in the field of digital twins and a simulation experiment.

The authors (Lu *et al.*, 2023) present a framework leveraging digital twin technology aimed at lowering management costs and enhancing the performance of satellite networks. The scheduling method operating within satellite systems is examined through its virtual representation and established for simulating and predicting the retransmission delay results. The simulation experiments have shown that the digital twin can reflect the scheduling behavior and predict the delay in dynamic environments.

A digital twin simulation system is developed and applied in experimental simulations of high-speed motor accidents, utilizing 3ds Max, Unity3D and C# in the article (Wu *et al.*, 2022). In the paper, a general, accurate and time-sensitive digital twin model of a motor is established for analyzing a fixed, separately excited DC motor on the laboratory bench and an experimental simulation application is conducted to accurately represent the parameters of the experimental data and the motor state of a fixed DC motor in real time.

The virtual simulation platform for experimental teaching was described in paper (Yan *et al.*, 2024), which was developed specifically to improve planning in assembly workshops while showcasing a practical example of digital twin integration in hands-on instruction and supporting students' theoretical and practical skills development. The main objective of the simulation experiment was to provide students with a virtual experimental environment in which they can validate different assembly line workshop scheduling strategies and refine the scheduling algorithm by seamlessly integrating virtual and real methods.

In the paper (Cao *et al.*, 2024), an experimental digital twin modeling method is proposed "for the transmission front and middle case assembly line" (Cao *et al.*, 2024). In the research, the architecture of the digital twin-based system is developed and the digital twin model is created by constructing the visualization, logic and data models of the assembly line. Finally, a simulation experiment is performed in a virtual environment to identify and analyze issues present in the current assembly line.

The paper (Jinzhi *et al.*, 2022) aims to investigate the concept of the Cognitive Digital Twin (CDT) and its core elements using a systems engineering approach. To support the development of the cognitive digital twin, a conceptual architecture is designed according to the ISO 42010 standard. Furthermore, an application framework using a knowledge graph is provided to guide the CDT applications. Additionally, a tool chain compatible with the framework is proposed to support the deployment of CDT. Finally, the authors validated the concept through a case study supported by simulation-based experiments.

The author of the article (Jiang, 2021) employs digital twin technology to develop the overall architecture of the operation and maintenance system for building construction controlled by the digital twin. In addition, an intelligent simulation of the building construction process is conducted, integrating digital twin technology into the management of smart building construction. Through simulation experiment research, the author concluded that the digital twin-based intelligent building construction management model, proposed in the paper, can support the deployment of intelligent construction process in many ways.

In the paper (Wu *et al.*, 2023), a robust real-time optimization method based on digital twins in the supply chain is proposed. Drawing on the quantitative logical relationship between production and sales within individual chains, a state space equation for the supply chain system was formulated, incorporating logical, structural and quantitative features. This equation was then used, along with twin data, to develop digital twins of supply chains (Wu *et al.*, 2023). The authors employed supply chain digital twins to continuously update and adjust system parameters in real time, enabling robust real-time optimization of the supply chain. At the end, the simulation experiment was carried out according to the example. Experimental results indicate that real-time parameter updates via digital twins assist enterprise managers in developing effective management strategies and successfully mitigating bottlenecks within the cake supply chain system.

The article (Raska *et al.*, 2021) presents approaches for reducing the volume of data generated during simulation optimization with a digital twin. The goal of the research was to test and modify various optimization methods and their settings that are suitable for discrete simulation optimization according to the Industry 4.0 concept. The methodology is validated through an application designed to manage the execution of parallel simulation experiments using a client–server architecture integrated with the digital twin. The proposed methodology minimizes data volume in simulation optimization by integrating global optimization strategies with programming methods and big data techniques.

The literature review demonstrates that simulation experiments are widely recognized as an effective approach for the development of digital twins. However, existing research does not adequately address the methodology for developing digital twins of business processes. Further studies should explore how simulation experiments can be improved with methodology for developing digital twins. For detailed analysis, a systematic literature review based on Kitchenham (2009) is suggested as future work. This review will provide a foundation for further research and experimentation.

Business Process of a Drone Production: A Case Study

This chapter describes the business process of drone production. For research purposes, a private, non-profit organization that conducts and supports industry-related and applied research and development in Switzerland was chosen as the use case. As already mentioned, the business process that the company is involved in is the production of drones. Figure (2) shows the production of drone wing and Figure (3) the business process model. The Figure (2) illustrating the production of a drone wing is important in this study as it visually represents a manufacturing process that was directly observed, ensuring that the analysis and methodology are grounded in real-world production conditions.

The production process spans multiple workstations and begins when an order message is received from the ERP system. The received message contains information about the part of the product to be manufactured. After receiving the information about the part of the product to be manufactured, the employee decides on the basis of his own experience and judgement on which printer he wants to start production. If the selected printer does not have enough material to print the part, the light on the printer door lights up red, signaling to the worker that the container with the printing material needs to be replaced. The light is connected to the printer's sensor. The sensor is aimed vertically at the filament roll (container) and measures whether the distance is small (the filament passes the point at which the laser is aimed) or larger (it bounces off the wall of the printer housing). The sensor directs the laser at the object and this light wave is reflected by another lens inside the sensor. The angle changes depending on the distance and eventually the sensor triangulates the actual distance based on this angle. If there is not enough material, the worker changes the material container and starts printing, otherwise printing starts immediately. The worker selects the print option via the NodeRed control panel and the printing begins. After the worker initiates the printing process, the printer starts up and begins printing the part that represents the drone's wing (as can be seen in Figure 2). Warming up the printer takes about 20 min and the printing process itself takes about 1.5 h.

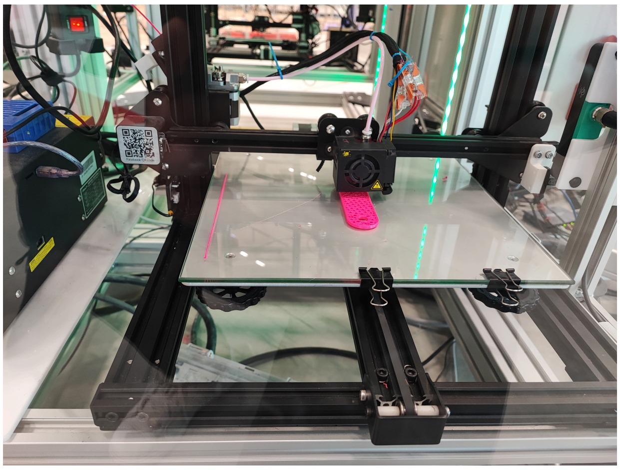

Fig. 2: Production of the drone wing

DOI: 10.3844/jcssp.2025.1379.1390

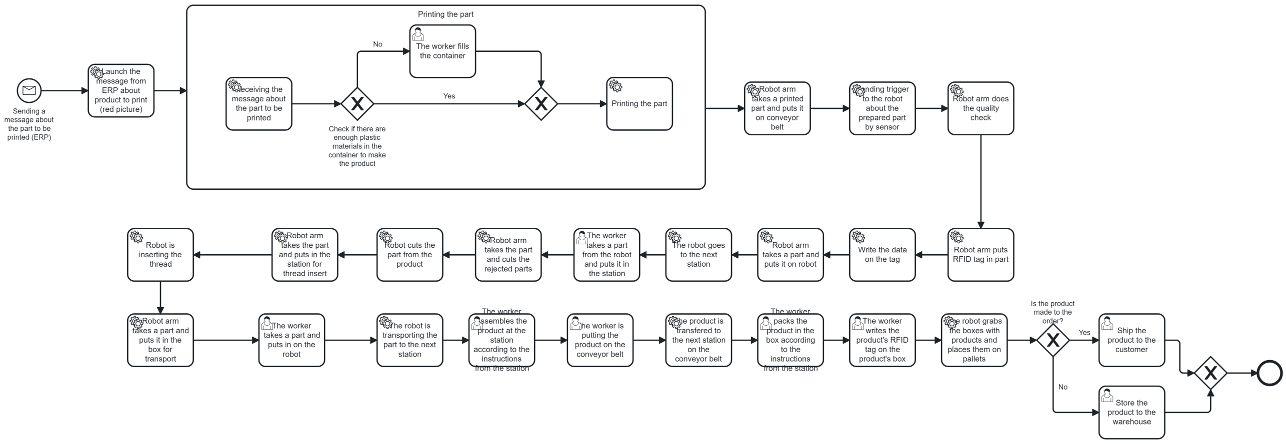

Fig. 3: Business process model of drone production

When the printer has finished printing a part of the drone wing, the sensor on the door of the printer lights up green, indicating that the printer is ready to print a new part. At the work station, the robot arm picks up the printed part of the product (drone) and places it on the conveyor belt. While the part is on the conveyor belt, the trigger is activated via the sensor and a message about the prepared part of the product is sent to the moving robot. The robot arm checks the quality of the manufactured part by scanning the part. If the manufactured part is OK, production continues. If the manufactured part is not of good quality, the production of a new part is started. The robot arm places an RFID tag on the correctly manufactured part and the data is written to the RFID tag. The robot arm places the manufactured part on the robot. The robot transports the part to the next work station. The worker takes the finished part from the robot and places it at the station. A robotic arm takes the part and shapes it.

Shaping a part means cutting off part of the product. The robot arm picks up the part and places it at the next work station. A robot arm threads the part. Next, the robot arm also picks up the part and places it in the transport box. The worker picks up the part and places it on the robot for transportation. The robot transports the finished part to the next work station. At a next work station, a worker assembles a product from parts, following instructions on the screen. While assembling the product, the worker must confirm on the screen that he has completed each suggested step and finally confirm that the product has been assembled according to the instructions. The worker places the finished product on the conveyor belt and the product is transported on the conveyor belt to the next work station. Finally, worker packs the product into a box according to the instructions on the screen at the work station. After the product has been packed, the worker must confirm on the screen that the product has been correctly packed according to the instructions. A worker writes the RFID tag of the product on the box. The robot arm picks up the product box and places it on a pallet with other product boxes. A worker checks whether the product was made to order. If so, the product is shipped directly to the customer. If the product is not made to order, it is stored until it is sold. At this point, the production process ends, which includes the assembly and packaging of the product.

Proposed Methodology of the Development of the Production Digital Twins

Business Process Management (BPM) is one of the effective organizational performance improvement methodologies used in the management of process-oriented organizations (Ubaid *et al.*, 2020). The authors (Szelągowski and Berniak-Woźny, 2024) conducted a systematic literature review with the aim of identifying the key obstacles and constraints in current approaches to BPM development from a researcher's perspective and defining the areas of key BPM changes needed for future BPM to meet the challenges of Industry 4.0 and the emerging Industry 5.0. If successfully implemented, BPM can lead to favourable results, as the focus is on the design of end-to-end processes (Neufeld and Deo, 2021). BPM uses the business process as a starting point and does not just focus on individual events. It should also optimize management as a goal and not just be satisfied with the processing of transactions (Ziqiang and Hong, 2010). There are several methodologies for modeling business processes.

According to Dumas *et al.* (2013) the life cycle of business process modeling consists of phases:

1. Process identification
2. Process discovery
3. Process analysis
4. Process redesign
5. Process implementation
6. Process monitoring

Process identification is the phase in which the business problem is posed. In this phase, the processes relevant to the business problem are identified, defined and interconnected. Process identification results in a newly created or revised process architecture that offers a comprehensive view of organizational processes and their interrelations.

Process discovery (often referred to as "as-is" process modelling) is a phase in which the current state of each of the relevant processes is usually documented in the form of one or more "as-is" process models.

In the process analysis phase, the problems associated with the current process are identified, documented and, where possible, quantified with the help of key performance indicators. Potential faults in the current processes are identified here (Neufeld and Deo, 2021).

Process redesign, also known as process improvement, focuses on identifying modifications that address previously detected issues and support the organization in reaching its objectives.

Process implementation is the phase in which the changes required to move from the current (as-is) process to the future (to-be) process are prepared and implemented. Process implementation includes two aspects: Organizational change management and automation. Organizational change management encompasses the activities needed to alter how all process participants perform their work. Process automation refers to the development and implementation of IT systems that support the future (to-be) process.

After the redesigned process is implemented, relevant data is gathered and analyzed to assess its performance against performance measures and targets. Bottlenecks, recurring errors or deviations from planned behavior are identified and corrective actions are taken. All of this is done in the process monitoring phase (Dumas *et al.*, 2013).

According to Laoyan (2025) the methodology for managing business processes includes the following steps:

1. Analysis: Analysis of business processes and their mapping from start to end
2. Modeling: Creation of a model of the business process in its current state
3. Implementation: Putting the business process model into practice
4. Monitoring: Monitoring the performance of the business process model using defined metrics
5. Optimization: Optimizing the business process model by eliminating identified inefficiencies

Both methodologies have similarities and the goal is the same: To eliminate the identified problems in the current business process and to optimize the future business process. The literature (Ubaid *et al.*, 2020) showed that the existing methodologies used for BPM implementation are either very old, do not cover human interaction with BPM systems or only partially describe the BPM methodology. The literature (Meziani and Saleh, 2011) argues that current business process methodologies lack the flexibility and agility needed, highlighting the need for novel approaches. New approaches to business process modeling are proposed in the literature (Meziani and Saleh, 2011) that aim to support a set of associated tools that promote the collaborative and incremental design and implementation of work processes. This is accomplished through the continuous modeling and implementation of business processes, guided by feedback from the real-world execution of the latest deployed processes.

Neufeld and Deo (2021) suggest the existing methodology stated by Dumas *et al.* (2013) should be improved with evaluation of organizational fit as the first step prior to beginning the process improvement methodology.

Following the examples of previous attempts, the existing methodologies for business processes management should be extended so that they correspond to the steps for developing a digital twin of the production business process.

Business process modeling represents a fundamental step in understanding, optimizing and digitalizing business activities, where business processes are documented, simulated and executed within an integrated framework. This concept can be visualized through a symbolic three-dimensional representation with three axes. The first axis, *a*, refers to the documentation of business processes, providing a static representation of processes using tools such as Microsoft Visio or similar modeling solutions. The second axis, *b*, encompasses the simulation of business processes, where key parameters such as activity duration and resource allocation are defined, enabling process dynamics analysis and performance optimization. The third axis, *c*, represents the execution of business processes, involving the development of process-oriented applications. At this stage, more complex data are incorporated, such as data models, form creation, business rule definition and other relevant elements that facilitate the operational implementation of processes through process-oriented applications.

The Figure (4) presents a symbolic three-dimensional representation of the position of business process digital twins in relation to the axes representing business process documentation, business process simulations and the execution of process-oriented applications.

According to Figure (4), within the three-dimensional space of this problem domain, the digital twin of the business process is located, which integrates all three levels: Business process documentation, business process simulation and the execution of process-oriented applications. The digital twin of the business process provides a comprehensive representation of the business process across its various stages, encompassing all three axes or components. The contribution of this approach lies in improvement of the business process management to a new, more complex level, thereby enhancing an organization's ability to respond effectively to contemporary business challenges and requirements. Additionally, the contribution of this research is in the advancement of business process modeling methodology to establish a methodology of the development of production digital twins.

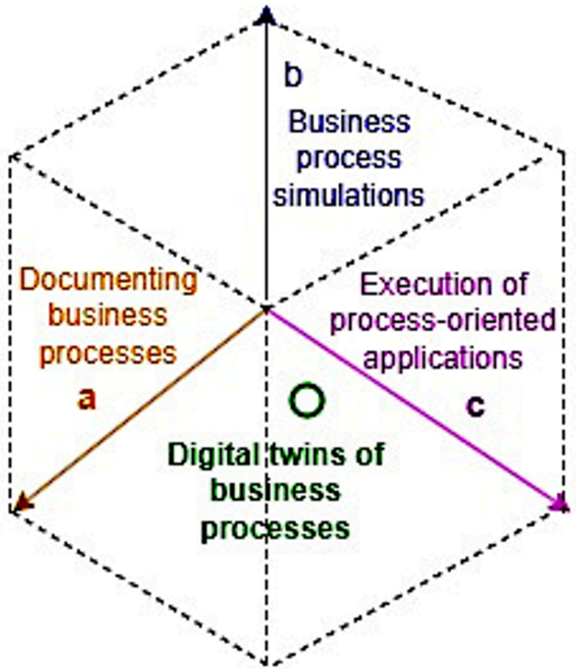

Fig. 4: The position of the digital twin of business process in relation to existing business process management approaches

Building on the existing methodologies (Laoyan, 2025) for business process management, a new methodology for the development of digital twins of production business processes is proposed, which is grounded in these established approaches. In this research, the following steps are proposed for developing a digital twin of a production business process:

1. Analysis: Analyze the production business process and record all activities of the production business process, i.e., map it from start to end
2. Modeling: Create a digital twin model of the production business process with regard to its current state
    1. Incorporate a more complex business rule into the digital twin model
    2. Incorporate the communication element of the digital twin model of the production business process with real IoT devices into the digital twin model
3. Implementation: Put the digital twin of the production business process into operation
4. Monitoring:
    1. Monitoring the performance of the digital twin of the production business process through defined metrics such as activity duration or resource consumption
    2. Compare the results of the simulated model of the production business process with the results of the digital twin of the production business process
5. Optimization: Optimize the digital twin model of the production business process by removing identified inefficiencies

The proposed methodology differs from other business process management methodologies as it includes, among others, the creation of a digital twin model of the production business process. The creation of the digital twin involves steps such as incorporating a more complex business rule into the digital twin model and incorporating the communication element of the digital twin model with real IoT devices. In standard modeling approaches, these steps are not typically included. However, in the development of a production digital twin, they are essential, as they enable communication between the digital twin and the external, real-world system.

Figure (5) illustrates the steps of the proposed methodology for the development of production digital twins, emphasizing the role of digital twin optimization. This step ensures that the production digital twin can effectively predict outcomes, enhance process efficiency and optimize decision-making. By continuously enhancing the model based on feedback loops and real-time data, the production digital twin becomes a very important tool for optimizing production processes and improving system performance in a dynamic environment.

The proposed methodology to create a digital twin of the production business process is tested using a simulation experiment to confirm that the digital twin follows the real business process in real time and is able to provide information for timely optimal decision-making.

DOI: 10.3844/jcssp.2025.1379.1390

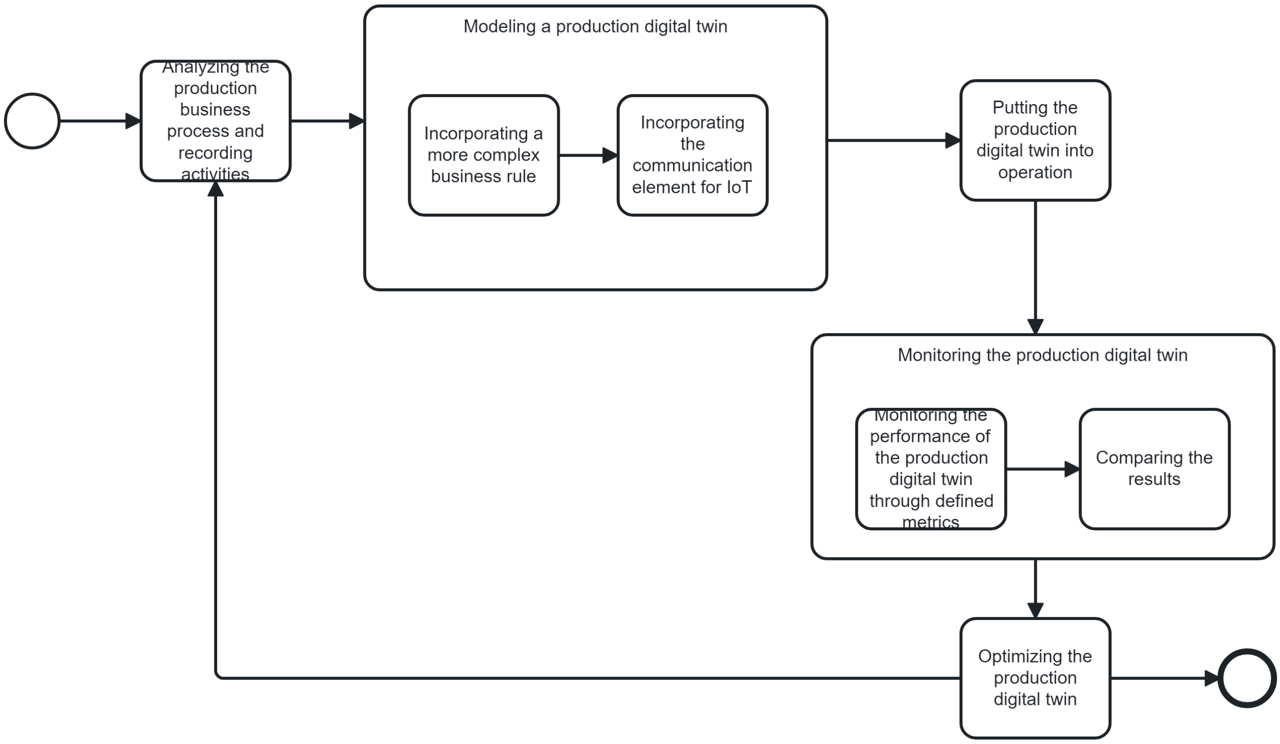

Fig. 5: Steps of proposed methodology of the development of the production digital twins

Digital Twin of the Production Business Process

A digital twin of the production business process was created in accordance with the methodology explained in the previous chapter. The aim of the simulation experiment in this study was to model and analyze a production business process. The digital twin was created in the Camunda platform. The Camunda process orchestration platform allows developers to model, automate and optimize business processes.

The production business process is managed using NodeRed, in which the flows of the entire business process are created. In order for Camunda to communicate with NodeRed, a bridge had to be created with a Python service that connects the two mentioned interfaces. This Python service facilitates communication by sending and receiving data through REST APIs, ensuring seamless interaction between the two systems. The Python service is employed as the intermediary due to its flexibility and ease of modification. This allows for extension and adaptation of the functionality without the need to alter the existing Camunda or Node-RED processes, ensuring minimal disruption while enhancing interoperability. The data for developing the digital twin was gathered in real time during the production process. Throughout its execution, the production digital twin seamlessly communicated with the sensor on the printer, enabling real-time monitoring and interaction. After starting production via the NodeRed system, Camunda also received live data, allowing the digital twin to monitor the process progress in real time. The execution log captured the sequential steps of the business process, showing how multiple instances were executed within Camunda. Before the part is sent to the printing, the system checks the required material quantity via the sensor. This information is acquired through the API and received by both NodeRed as well as Camunda. Here, the API response indicated that there was enough material. The process continued through predefined steps, ensuring that operations proceeded as expected. The system then initiated the printing operation, marking the transition to the next phase of execution. Upon completion, the process instance was successfully finalized. This confirmed that the digital twin accurately reflected real-world operations and followed predefined decision rules for handling material shortages.

The purpose of the digital twin of the production business process is not only to monitor the status of production, but also to react in good time to possible difficulties, e.g., a shortage of production material. The digital twin monitors the production quantity, the production time and simultaneously knows how much material is required for the production of which part and how much material is still available. In the event of an imminent breakdown due to a shortage of material to complete production, the digital twin will report that the material container for production will soon need to be replaced.

In this use case, the study aimed to test whether the digital twin effectively communicates with the real production business process in real time and can promptly provide information to enable timely decision-making.

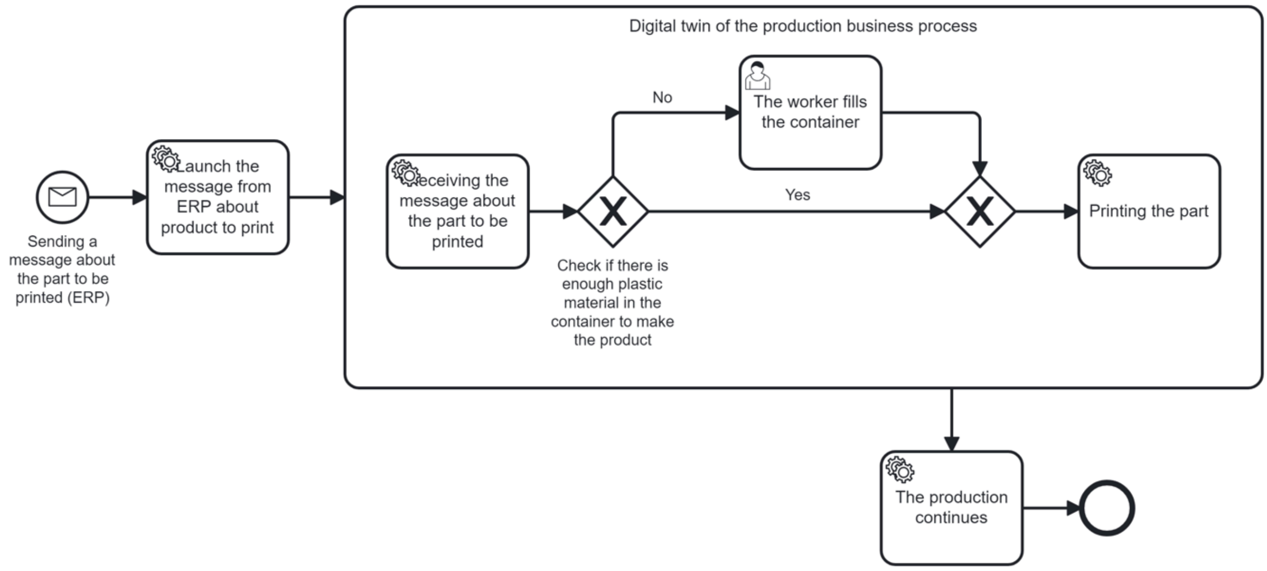

Fig. 6: Digital Twin of the Production Business Sub-Process

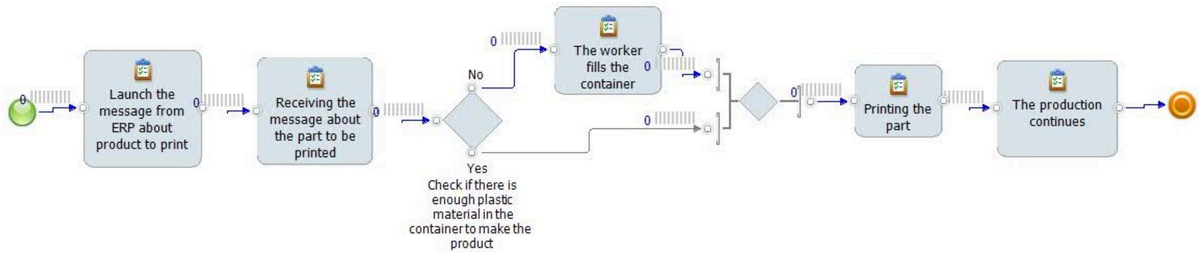

Fig. 7: Simulated model of the production business process

Figure (6) represents the model of the digital twin of the production business sub-process related to the production of drones. A digital twin model was created to monitor the production of a drone component, with data collected from the production line in real time to track the production status. The results are monitored production and information about the production line that is used to make operational decisions.

Comparison of the Results of the Simulated Model with the Results of the Digital Twin of the Production Business Process

In order to confirm the simulation experiment, a simulated model of the production business process was created in IBM WebSphere 7.0 and the results of the simulation were compared with the results of the digital twin. To create the simulated business process model, historical data gathered from observing the real-world process was used.

Figure (7) and Table (2) show the results of the simulated business process model. Figure (7) illustrates the simulated model of the business process, for which the simulation was conducted with a single token. Table (2) shows the results of the dynamic analysis indicating the duration of each activity in the process. Table (2) presents quantitative data on the duration of different activities within the drone production process simulation. The two key time metrics recorded are average elapsed duration, which represents the average time taken from the start to the completion of an activity, including any delays, idle time, or waiting periods and average working duration, which measures the actual time spent actively working on the activity. From the data table, it is evident that for most activities, average elapsed and average working durations are identical, indicating that there were no significant delays or idle time. This suggests an efficient process where work is continuously executed without interruptions. The printing activity takes 1 h and 50 min for both elapsed and working duration, indicating

DOI: 10.3844/jcssp.2025.1379.1390

that no delays occurred and printing started immediately and continued without interruption. Similarly, receiving the message about the part to be printed shows an elapsed and working duration of 1 sec, meaning the message was received without any waiting time. The worker filling the container takes 5 min for both elapsed and working durations. The most time-consuming activity is printing the part, which takes almost the entire process duration. Other steps, particularly message exchanges and material checking, occur almost instantaneously, reinforcing the efficiency of automated communication in the system. The results suggest that the drone production process is highly optimized, with minimal idle times.

Since the actual drone production process takes approximately 1 h and 50 min, plus an additional 5 min for the worker to refill the container, it can be concluded that the digital twin faithfully replicates the real-world process in both duration and execution. The simulated model, developed based on historical data, shows no deviations in relation to the execution of the digital twin of business process. In other words, the digital twin of the production business process aligns appropriate with both the simulated model and the real business process. The key distinction, however, lies in the digital twin's ability to communicate in real-time with its physical counterpart, unlike the simulated model, which operates based solely on predefined data and scenarios.

Table 2: Results of the dynamic analysis

Case name	Activity name	Average elapsed duration	Average working duration
Case 1	Drone production	1h 55 min 2 sec	1h 55 min 2 sec
	Check if there is enough plastic material in the container to make the product	0 sec	0 sec
	Launch the message from ERP about product to print	1 sec	1 sec
	Merge	0 sec	0 sec
	Printing the part	1h 50 min	1h 50 min
	Receiving the message about the part to be printed	1 sec	1 sec
	The production continues	0 sec	0 sec
	The worker fills the container	5 min	5 min
All cases		1h 55 min 2 sec	1h 55 min 2 sec

Results and Discussion

In this study, the simulation experiment was investigated as a method for developing digital twins of the production business processes. The research question, "1. What are the key steps involved in the methodology for developing production digital twins?" is answered in chapter *Proposed methodology of the development of the production digital twins*, where the methodology of the development of the production digital twins is proposed. The proposed methodology is based on existing methodologies for business process management, but is extended to include the steps required to develop a functional digital twin of the production business process that replicates the actual state of the production system. The answer to the research question "2. How can the developed methodology be used to create a digital twin of a production business process?" is given in chapter *Digital twin of the production business process*, where a digital twin of the production business process is developed that communicates in real time with the real business process and monitors the production flow. In the mentioned chapter, a digital twin of production business process was created in Camunda and a Python script was used as a bridge between Camunda Modeler and NodeRed, which contains the flows of the real business process.

The proposed methodology for developing production digital twins builds upon existing business process management frameworks but introduces key enhancements to address the challenges identified in previous studies. Prior research has explored digital twin applications in various domains, such as manufacturing, supply chain optimization and intelligent building construction, often focusing on simulation experiments to validate and optimize digital twin models. However, a notable gap in the literature exists regarding a structured methodology for developing digital twins specifically for production business processes. A structured methodology for developing production digital twins was outlined, detailing each step necessary to ensure an accurate and efficient digital representation of the physical production system. The development of a digital twin model demonstrated the potential to improve decision-making, optimize processes and increase overall system performance. The proposed methodology not only facilitates real-time monitoring and simulation, but also enables predictive analysis and operational adjustments, which are crucial for modern production environments. By comparing the results of the simulated model with the developed digital twin, this study demonstrates that the digital twin not only accurately replicates the real-world production process but also enables real-time monitoring and decision-making. Unlike traditional simulations that rely on predefined data sets, the digital twin dynamically interacts with the physical process, continuously updating its state based on real-time data. The key contribution of this study is a methodology that extends existing BPM frameworks to provide a practical approach for developing a production digital twin. This advancement is particularly relevant in the context of Smart Industry, where real-time adaptability and optimization are critical. By addressing the limitations of previous methodologies, the proposed approach not only improves the precision of digital twins but also enhances their practical applicability in production environments.

Conclusion

Real-time execution of digital twins faces several bottlenecks. For example, data acquisition challenges, such as sensor latency, data overload and inconsistent data quality, can hinder accurate real-time updates. Furthermore, integration with legacy systems and interoperability between different frameworks create synchronization difficulties, while decision-making bottlenecks arise from delayed responses to anomalies. Additionally, scalability and maintenance become challenging as digital twins grow, demanding efficient resource allocation, continuous model updates and adaptive AI-driven optimizations. For these reasons, future work requires further investigation in areas such as the integration of more advanced machine learning and artificial intelligence techniques to improve the adaptive capabilities of digital twins. Exploring the application of digital twins in broader contexts, such as cross-industry collaboration and supply chain optimization, could open up new avenues for innovation in digital twin technology.

Acknowledgement

Authors are grateful to reviewers for their valuable comments.

Funding Information

The publication of this research paper is funded by the authors' organization.

Author’s Contributions

All authors have contributed to the originality of the work with their suggestions, research and description of the results.

Ethics

This article is original, contains unpublished material and involves no ethical issues. The corresponding author confirms that the co-author has read and approved the manuscript.

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