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Partial Twin – Pragmatic Digital Twin Adoption for SMEs

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Abstract

With the help of digital twins, processes can be simulated and tested in a digital environment prior to conducting real-world tests, which often incur significant costs and use of resources. However, developing digital twins frequently entails complex, customized, and costly implementations, making it an impractical option for many small and medium-sized enterprises (SMEs). This paper proposes the idea for an affordable and easy-to-implement version of the digital twin, particularly tailored for manufacturing sectors, termed the “Partial Twin”. The Partial Twin serves as a digital counterpart to a production site or its components, primarily based on numerical data. It aims to strike a balance between simplicity and necessary complexity, ensuring efficient representation and control options while lowering entry barriers. Designed for adaptability, it enables SMEs to incrementally implement digital capabilities, focusing on essential functionalities such as dynamic production planning and optimization. This paper validates the concept through a literature review, explores potential implementation strategies, and outlines the characteristics of the Partial Twin.

1. Introduction

Digital twins have become a widely discussed topic in research, particularly within the manufacturing sector. Jyeniskhan et al. (2024) highlight an exponential increase in publications and citations related to digital twins over the past decade. Furthermore, Alnowaiser and Ahmed (2023) report that from 2017 to 2021, 33% of digital twin research was dedicated to smart manufacturing. A more recent study by Dihan et al. (2024) reveals that 43% of digital twin research originates specifically from the manufacturing domain. Digital twins enable real-time monitoring to support data-

driven decision-making, facilitate predictive maintenance to minimize downtime and costs, optimize production processes through simulations, and provide a virtual environment for testing new strategies and designs prior to their implementation (Botín-Sanabria et al., 2022; Dihan et al., 2024; Hakiri et al., 2024; Zhang, 2024, pp. 4–8). As a transformative technology, digital twins have gained significant attention for their promising potential. However, despite their long-term benefits, the comprehensive implementation of digital twin solutions remains challenging. Creating a complete digital twin for an entire production site presents a complex, resource-intensive, and costly undertaking. Key obstacles include the need for specialized expertise, potential investment in new sensors, and additional computational resources (Botín-Sanabria et al., 2022). Consequently, SMEs often hesitate to adopt digital twin solutions for managing their production processes (Hananto et al., 2024; Jyeniskhan et al., 2024; Uhlemann et al., 2017). Nevertheless, like larger enterprises, SMEs also require enhanced digitalization to improve production efficiency. In response to these challenges, several approaches have emerged to make digital twins more accessible to SMEs. For instance, some studies propose a business model for a “Lightweight Digital Twin as a Service” or platform-based solutions aimed at improving cost efficiency (Guo et al., 2023; Marra et al., 2024). Others have focused on making the integration of digital and physical assets easier (Yasin et al., 2021) or examined how a paid “Digital Twin as a Service” offering can reduce entry barriers for SMEs (Schmid et al., 2024). These approaches provide a foundation for developing digital twin models, particularly tailored for SMEs. However, they predominantly emphasize the creation of highly detailed digital twins, which can lead to

complexities in implementation and a strong demand for granular data. Furthermore, existing models are typically structured within predefined pricing frameworks that contradict the necessity for cost-effective digital twin solutions for SMEs. To enhance the applicability of digital twins in SMEs, it is crucial to provide multiple development pathways, allowing for greater flexibility and adaptability to various operational needs. Consequently, there is a pressing need for accessible and swiftly deployable solutions to bridge the gap between current operational realities and the envisioned comprehensive digital twin.

Moreover, a recurring challenge highlighted in the literature is the lack of generalizable concepts and standardized interfaces in most digital twin research. This issue, already identified by Kritzinger et al. in 2018, remains unresolved (Alnowaiser & Ahmed, 2023; Botín-Sanabria et al., 2022; Hakiri et al., 2024; Hananto et al., 2024; Kritzinger et al., 2018; M. Liu et al., 2021; Yao et al., 2023; Zhang, 2024, p. 16). That is why, for example, Hananto et al. (2024) suggested introducing a clearer definition for better differentiation within the digital twin domain, e.g., “3D digital twin” for what is commonly referred to as a “digital twin”.

This introduction is based on a forward-backward literature review approach. The keywords “Digital Twin” in the context of “Manufacturing Planning” and “Management” initiated the literature search. Targeted combinations of the term “Digital Twin” with keywords such as “application”, “integration”, “implementation”, “development”, “technologies” were examined to collect insights based on their practical applications. Additionally, the keyword combination “digital twin” and “SMEs” was used. The resulting research references were the starting point for this forward-backwards search.

According to the identified research gaps, we will follow these research questions (RQ):

- RQ1: How can the digital twin approach for manufacturing be modified and named to provide essential functionalities while ensuring a more accessible, expedited, and cost-efficient implementation for SMEs?
- RQ2: What functionalities should it possess, and what steps are necessary to implement these functionalities?

2. Methods

The literature review has revealed a significant gap between the capabilities of SMEs and the requirements for implementing digital twins in the manufacturing sector. The high initial costs and inherent complexity associated with digital twin adoption often render it impractical for SMEs. To

address these challenges, we propose a framework designed to provide an overview of the production site’s status while facilitating automated planning and control.

In Section 2.1 we will introduce the fundamental concepts underpinning digital twins. Section 2.2 will define the key properties of our proposed framework, elaborating on its design, functionality, and potential implementation. Furthermore, in Section 2.3, we will position our solution within the digital maturity model of digital twins as articulated by Liu et al. (2024). Finally, Section 2.4 presents potential use cases to enhance conceptual clarity.

2.1. Digital twin

The term “digital twin” can be defined in various ways. Its origins trace back to Dr. Michael Grieves, who first introduced the concept in 2002 (Grieves, 2016). Initially, it was defined within the context of product life cycle management as “a set of virtual information constructs that fully describes a potential or actual physical manufactured product” (Grieves, 2016, p. 2). Today, the digital twin paradigm extends to multiple domains, including supply chain management (Hong Lim et al., 2021), circular economy (Meng et al., 2023), smart cities (Adreani et al., 2023), vertical farming (Monteiro et al., 2018) and 3D-printing (Hananto et al., 2024). Consequently, definitions of digital twins vary significantly. For instance, Dihan et al. characterize it as “a digital copy or virtual representation of an object, process, service, or system in the real world” (Dihan et al., 2024, p. 2). In contrast, Hakiri et al. describe the digital twin as “a virtual replicate of the real-world system that receive data from the physical system and send decisions to perform closed-loop control” (Hakiri et al., 2024, p. 4). A “closed-loop system” allows for bi-directional data exchange between the digital counterpart and the physical entity it represents (Alnowaiser & Ahmed, 2023; Hakiri et al., 2024; Y. Liu et al., 2024). By creating these virtual replicas of physical assets, digital twins facilitate real-time monitoring and analysis of KPIs, enabling informed decision-making. This capability, for example, supports predictive maintenance, which reduces downtime and operational costs. Additionally, digital twins contribute to the optimization of production processes through simulations that identify inefficiencies and potential improvements. They allow organizations to test new strategies and designs in a risk-free virtual environment before implementing them in the physical world (Zhang, 2024, pp. 4–8).

Digital twins can manifest in various forms, such as augmented reality (AR) interfaces or three-dimensional visualizations that mirror their physical counterparts (Mishra et al., 2024, p. 2), and are often recognized as a detailed digital representation of machinery (Hananto et al., 2024). However,

formal definitions suggest that a digital twin may encompass a broad array of concepts, including the digital representation of a physical object, a process, or a product (Dihan et al., 2024). Therefore, the notion of a digital twin is expansive, integrating multiple paradigms.

2.2. Partial Twin

To enhance applicability for SMEs, our approach presents a simplified and more targeted version of a digital twin tailored specifically to SMEs in the manufacturing sector. While the broader concept of the digital twin encompasses various industries and highly detailed models, our model focuses on practical, cost-effective solutions that address the challenges faced by smaller manufacturing enterprises. In the future, this approach could potentially be adapted for other domains.

Therefore, we would like to introduce the concept of the “Partial Twin”. This paper outlines an initial framework for this approach and proposes further steps toward its practical implementation. The Partial Twin serves as a streamlined, early-stage alternative to traditional digital twins, providing an accessible and affordable solution for SMEs. By doing so, this research contributes to the development of best practices for adopting digital twins in manufacturing environments of SMEs. The positioning of our approach is depicted in Figure 1.

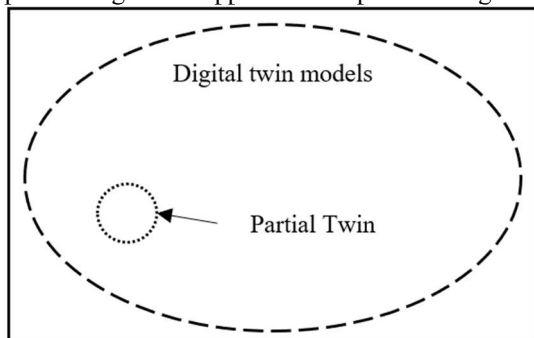


Figure 1: Positioning within the general digital twin approach

2.2.1. General properties

The proposed Partial Twin should be an affordable and easy-to-implement solution for the digital management of production sites. It is meant to provide a digital representation through, specifically KPIs or diagrams, including the ability to control the factory. Unlike most known digital twin models, which offer comprehensive real-time simulations and detailed object behavior often governed by physical laws, the Partial Twin focuses on integrating the data sources into a unified platform, to be used as a tool for automated planning and scheduling optimization. This information should be visible on a schematic overview of the factory by KPIs. Since it covers only a subset of the functionalities typically performed by a digital twin, it is called the “Partial Twin”.

A dashboard also provides detailed insights into the production site, but it lacks the capability to perform simulations or actively manage production processes. This paper makes use of dashboards for comparative purposes. Differentiation of key characteristics for dashboards, Partial Twin and digital twins can be observed in Figure 2 and Figure 3. Accordingly, Figure 2 illustrates the characteristics in a simplified form, while Figure 3 presents a morphological matrix to elucidate the principal attributes of the Partial Twin. The concept aims to combine the intuitive and simplified form of visualization that a traditional dashboard offers, with the advanced planning and management capabilities of a digital twin according to the needs of SMEs (Hananto et al., 2024). The new approach is envisioned as pre stage toward digital twin adoption, offering a practical transition solution for companies not yet ready for the full complexity of digital twins or companies for which a full digital twin would be too excessive. The Partial Twin is a specified version of the digital twin, intended to differentiate it from the broader digital twin concept. The representation should be less detailed as for the original digital twin but still facilitate bi-directional data exchange, thereby functioning as a closed-loop system in the easiest possible way. By providing a flexible platform approach, the framework encourages continuous improvement and allows for the gradual integration of new factory components, thereby enhancing adaptability. It should also serve as guidance for accessing relevant data sources that may already be collecting useful information for constructing the Partial Twin. Additionally, this framework aims to provide differentiation through a clear and new name, addressing the current ambiguity in naming various digital twin technologies (Hananto et al., 2024).

2.2.2. Implementation Ideas

In leading to possible implementation options, it is crucial to keep the perspective of the addressed companies in mind. They are SMEs constrained by limitations, in money, time and expertise regarding implementing a digital twin for factory control. The core idea is to develop a Python framework that defines the necessary interfaces for data access from existing systems, consolidating all important data and allow adaptability, such as adding production components later. The framework should also provide a user-friendly graphical user interface (GUI) that not only displays production metrics, but shows and explains the production plans. An agile approach can facilitate implementation, carefully considering both

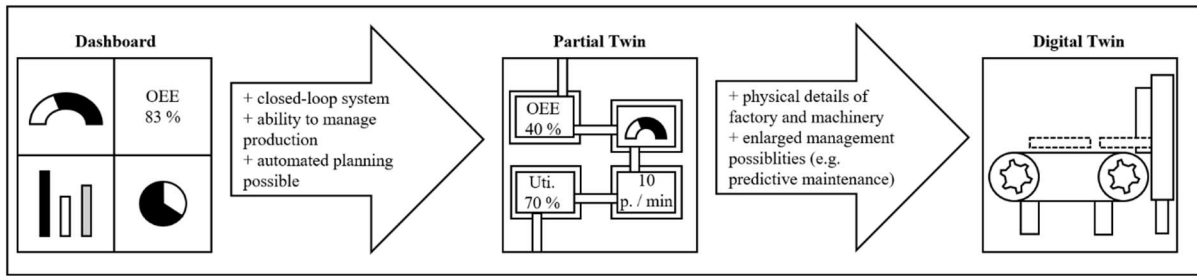


Figure 2: Simple morphology for Dashboard, Partial twin and Digital Twin

associated cost and efforts involved (Beck et al., 2001).

Moreover, it is essential to consider an effective computer architecture to support this framework. Insights from Dihan et al. (2024) can offer further ideas regarding which methods to employ. For centralized data collection, employing a knowledge graph approach may provide a flexible and interconnected method for data storage, enhancing visibility and transparency. Potential downsides, particularly relating to large data volumes and implementation effort needed to set up a knowledge

journey (Beck et al., 2001). Ideally, example companies should be involved during development to identify and address challenges that may arise during implementation.

2.2.3. Implementation phases

The implementation requires developing structured phases, allowing for the gradual integration of the framework. While there is no universally accepted process model for implementing a digital twin, the phases described in the literature exhibit a similar structure and share common steps. Sommer (2024) identified five key phases by analyzing various

	Expressions		
Characteristics	1	2	3
Depiction of factory	No depiction of factory	Schematic overview of factory	Mirroring of the machinery / factory quite detailed
Detail of depiction	KPIs / numbers	Diagrams	All physical details of the machine
Detail of machinery shown	None	Machinery icons / sketch	Representation of most physical details and functionalities of machinery
Time reference	Historical view	As close to real-time as possible	Real-time
Closed-loop system / Bi-directional data exchange	No	Yes	Yes
Data requirements	Historical data	Historical & real time data of medium detail	Detailed historical & real time data
Ability to control / manage factory	No	Yes	Yes

Dashboard
 Partial Twin
 Digital Twin

Figure 3: Morphological matrix comparing Dashboard, Partial Twin and Digital Twin

graph or ontology should be carefully assessed (Dihan et al., 2024; Lippolis et al., 2025; Yang et al., 2025). Furthermore, the creation of an ontology could facilitate condition monitoring similar to models discussed by Cao et al. (2019), while also incorporating planning and control functionalities for production processes. Existing approaches aimed at democratizing digital twins for SMEs (Marra et al., 2024; Schmid et al., 2024; Yasin et al., 2021) should also be carefully examined for potential synergies. Additionally, simulation techniques can be employed for production scheduling to integrate crucial information for improved operational efficiency. By treating the Partial Twin as a dynamic software project, organizations can adopt an agile methodology that embraces iterative development and continuous improvement throughout the implementation

implementation approaches: “(1) Definition/Initiation”, “(2) Design/Development/Planning”, “(3) Use/Scaling/Implementation”, “(4) Controlling/Review/Validation”, and “(5) Closing/Lessons Learned”. In contrast, Fett et al. (2023) proposed a more detailed framework consisting of seven “procedure steps” for digital twin modeling, emphasizing the creation process of the digital twin itself. Similarly, Jin et al. (2024) presented a case study from the additive manufacturing industry, outlining a nine-step implementation process, which provides a more granular perspective compared to Sommer’s five-phase approach (Fett et al., 2023; Jin et al., 2024; Sommer, 2024).

Based on these findings, the following five phases are suggested for implementing the Partial Twin:

1. Status quo
2. Design
3. Implementation
4. Operational use
5. Continuous improvement

Initially, the assessment of the **status quo** focuses on identifying existing data sources by examining what data is already collected and where it is obtained. It is essential to define the current landscape of company systems. This is followed by a **design** phase, in which it is defined what additional data should be collected in the future. During this phase, it is critical to identify relevant KPIs and establish how to respond to specific values (e.g., whether they are too high or too low) concerning the factory control system. The subsequent **implementation** phase involves the integration of this data into the model, including establishing connections via APIs and deploying the necessary infrastructure. After implementation, the **operational use** phase begins, during which the digital twin is actively employed to support decision-making processes and optimize workflows. The final phase, the **continuous improvement phase**, focuses on ongoing refinement of the system and the integration of new data sources to continuously enhance efficiency, accuracy and the overall impact of the system.

2.3. Maturity stage of the Partial Twin

To gain a clearer perspective on the capabilities of the Partial Twin, it should be positioned within the “Digital Twin Maturity Model” (DTMM) introduced by Liu et al. (2024). To create their maturity model, they consolidated different maturity models from the literature, based on the capabilities and definitions of different digital twin models. The DTMM defines maturity levels based on a model’s capabilities. Here, “capability” encompasses the range of functions a digital representation of an object can perform. The authors categorized them on a **scale from low to high capability**, beginning with the classification “No Twin”, which is equal to no capability. According to Lui et al. (2024), the subsequent capabilities on the scale are “Data Management”, “Modeling”, “Two-way Communication”, “Simulation Activities”, “Full Life Cycle Management”, “Human Machine Interface”, “Intelligent” and “Integration”. Each level introduces more functions and complexity than the preceding one.

After classifying the models from the reviewed articles according to the capability scale, the authors inferred the following five levels for their DTMM:

- Level 0: Digital Model
- Level 1: Digital Shadow
- Level 2: Digital Twin
- Level 3: Cognitive Digital Twin
- Level 4: Federated Digital Twin

A key distinction in this maturity model is that “Digital Model” and “Digital Shadow” feature one-directional data flow, whereas “Digital Twin” incorporates bi-directional data flow. In addition, the “Digital Twin” should cover monitoring and control of the physical counterpart, as opposed to the “Digital Model” and “Digital Shadow”. The “Cognitive Digital Twin” and “Federated Digital Twin” level represent more advanced and intelligent versions of digital twins, incorporating greater autonomy, interactivity, and data-driven decision-making capabilities (Y. Liu et al., 2024).

The “Digital Twin” level typically requires the capabilities “Two-way Communication”, “Simulation Activities”, “Full Life Cycle Management” and “Human Machine Interface”. The Partial Twin meets the first two criteria but lacks the latter two. Thus, it qualifies as a digital twin but represents a more specialized variant. This distinction underscores our framework’s goal of refining the digital twin concept, aiming to provide a more applicable version for SMEs.

2.4. Example use cases for Partial Twin

The Partial Twin can serve a variety of purposes, including monitoring, analysis, and optimization. Another potential use case for the Partial Twin is the automated planning and optimization of production processes. By creating a Partial Twin of a production line, organizations can analyze real-time data to enhance efficiency, reduce waste, and improve resource allocation. This dynamic model allows for the simulation of different production scenarios, enabling proactive decision-making. In the next step, the prediction of both the current state and future conditions of the factory can be enhanced through the use of machine learning (ML) and artificial intelligence (AI). By leveraging historical and real-time data, ML algorithms can identify patterns and forecast future performance, allowing for timely interventions and minimizing downtime.

3. Results and Discussion

In response to RQ1, this paper presents the concept of a modified digital twin approach termed “Partial Twin”. This approach aims to provide a specific digital twin application that enhances the accessibility, expedites implementation and improves cost-effectiveness of digital twin technology in the manufacturing for SMEs. The Partial Twin serves as a digital representation of the factory, incorporating KPIs within a closed-loop system.

To address RQ2, we identify several key attributes essential for the functionalities of our Partial Twin. It must effectively represent a factory digitally through a Python framework, offering a GUI to present an overview of factory and machinery's KPIs, along with a drill-down option for in-depth analysis. The system should be straightforward to implement, utilizing an agile approach. First, a thorough examination of the existing system landscape and the data currently being collected is crucial. This should be followed by a theoretical design of the Partial Twin, where critical KPIs are identified, and additional data requirements are established. Further considerations include configuring the system to determine which areas or components of the production process should be represented in the Partial Twin. After the design phase, the implementation and deployment of the system should commence, leading to its operational utilization and ongoing engagement in a continuous improvement process.

In summary, here is a list with all essential characteristics of the Partial Twin:

- New name for better differentiation: Partial Twin
- Digital representation of a factory with less detail compared to a full digital twin
- Closed-loop system facilitating bi-directional data exchange
- Capable of managing and control the factory or parts of it
- Python framework (incl. APIs & GUI for overview of the factory and machines)
- Designed for easy implementation by providing guides
- Focused on continuous improvement with an agile approach

In Section 2.3, our framework is positioned within a Digital Twin Maturity Model, demonstrating that it qualifies as a digital twin, by definition while also aiding in the differentiation of digital twin models based on their capabilities. Furthermore, Section 2.4 presents example use cases of the framework.

To validate the methodology and approach for developing the framework, existing frameworks, such as those examined by Hakiri et al. (2024), will be evaluated and utilized as foundational references. At this stage, the research remains theoretical and does not yet have direct practical applications. Future work will focus on prototypical implementation and testing within a company environment.

A critical aspect requiring further exploration is the precise definition of the tasks the Partial Twin should support, such as production planning.

Additionally, during the setup and implementation phases, it will be essential to identify which data and data sources are crucial at different maturity stages of the Partial Twin. Enhanced differentiation in these stages could provide entry points for companies at varying levels of digitalization.

Moreover, considerations regarding the trustworthiness of digital twin models, as highlighted in recent studies (Hakiri et al., 2024; Kumar & Agrawal, 2024; Y. Liu et al., 2024), will play an integral role in our framework.

One notable limitation is the potential lack of internal access to company systems, which may complicate the frameworks development. However, this challenge also serves as motivation to maintain a generalized approach. It is essential to recognize that the successful adoption of digitalization in production heavily relies on the management's willingness to invest in these initiatives. While streamlining the implementation process is vital, a certain commitment will always be necessary. Nevertheless, the iterative approach should aim at achieve quick wins fostering ongoing engagement. Effective data pipelines are crucial; without some degree of prior digitalization of the factory, the proposed framework cannot function effectively. It also is important to note that cultural factors related to user acceptance, which are critical during the implementation of new software systems, have not been addressed in this study (Wallace & Sheetz, 2014). Conversely, the opportunities presented by this research include the facilitating a continuous improvement process that can enhance acceptance among users, as their familiarity with the software grows alongside its impact on their work. Additionally, the framework promotes easier access to advanced planning methods, promoting diversity within the organizational landscape and aiding smaller enterprises in catching up. Overall, these findings provide valuable insights for integrating the Partial Twin into manufacturing processes for SMEs and contribute to establishing competitive advantages in an increasingly digitized economy.

4. Limitations and Conclusion

In summary, the most significant outcome of this research is the introduction of the "Partial Twin" approach, designed to facilitate the adoption of digital twin technologies by SMEs. A primary distinguishing feature of the Partial Twin is its less intricate design compared to most established digital twin models. It emphasizes the display of essential KPIs of a factory while still progressing towards a closed-loop system. With its agile methodology, this approach provides a more accessible and straightforward alternative to traditional digital twin implementations, thereby enabling SMEs to engage with and adopt it successfully. Ultimately, it aims to enhance their

competitiveness in an increasingly digitized marketplace.

One limitation of this work is that successful digitalization in production is heavily reliant on management's willingness to invest in such initiatives. While streamlining the implementation process is essential, some effort will always be required, necessitating an iterative approach focused on achieving quick wins to maintain engagement. This paper presents the theoretical idea for a framework and highlights the need for further research and future implementation.

Future research will focus on several critical next steps to advance and implement the Partial Twin framework. Initially, a prototype will be designed in collaboration with industrial partners to gather real-world experiences, which will subsequently be synthesized into guidelines and best practices that facilitate learning from past challenges. A fundamental aspect of this research will involve identifying criteria that delineate when a Partial Twin has reached sufficient maturity and when it should transition into a full digital twin, particularly as production sites or the complexity requiring management by the system increases. Additionally, the research may yield a generalizable framework if the prototype proves successful. From a practical perspective, this research holds promise for creating tangible use cases within companies to support SME manufacturing firms. Investigating effective methods to integrate AI into the Partial Twin, as highlighted by Alexopoulos et al. (2020) will also be essential.

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