LITERATURE REVIEW AND COMPARISON OF DIGITAL TWIN FRAMEWORKS IN MANUFACTURING

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KEYWORDS

Digital Twin, Industry 4.0, Smart Manufacturing, Industrial Framework.

ABSTRACT

Industry 4.0 technologies have led to the affirmation of the Smart Manufacturing. In this paradigm Digital Twins (DTw) are defined as simulation models that are both getting data from the field and triggering actions on the physical equipment. With this paper, our aim is to extend the existing analysis of DTw in manufacturing from a technical and architecture point of view, trying to define correlations among DTw features. This work proposes a new framework, illustrating three reference architectures for the DTw that could help to define a guideline for the design and implementation of this technology. The results found are proposed as a driver for future research, aspiring to identify an architecture enabling a complete integration between DTw in manufacturing systems.

INTRODUCTION

In recent decades, a mass demand market and fast changing environment has put forward the need of flexibility and interoperability within the manufacturing field. A greater amount of information, obtained with the computing power from industrial equipment, needs to be processed and managed. Indeed, the industry 4.0 (I4.0) paradigm has paved the way for the concept of "smart factory" (Villalonga et al., 2020), a flexible environment that creates the conditions for a highly modular and digitalized production facility (Negri et al., 2020) that responds in real time to meet the changing demands and disruptions in the factory, supply network, and customer requirements (Yang et al., 2022). In such a context, simulation becomes an increasingly useful and important tool. The main enabling technologies of the I4.0 are the basis for a new simulation approach, which leverages on the pervasive connectivity in production systems to offer a real-time synchronization with the field (Cimino et al., 2019) and replicate real world behaviours in virtual environments.

However, synchronization requires full data models to be simulated. This issue led to the concept of Digital Twin (DTw) in manufacturing (Rocca et al., 2020), considered as the "cyber" side of the Cyber Physical Systems (CPS), the core to achieve smart manufacturing (Zhuang et al., 2018). Defined as a digital copy of a physical asset, DTw is a system that can replicate, plan, control and directly interact with its physical side.

However, a univocal definition of DTw does not exist, and no common understanding concerning this term can be found since it is used differently over disparate disciplines (Negri et al., 2020).

In this sense, some influential DTw reviews have made their contribution in the literature. Among them, (Kritzinger et al., 2018) proposes a classification of DTw into three subcategories, focusing on the data exchange between the Physical and the Digital object. Based on this, (Cimino et al., 2019) introduces a review of DTw applications in manufacturing. Lastly, (Semeraro et al., 2021) tries to collect over 30 DTw definitions found in literature, generalizing them in a common definition. Despite their contribution, DTw concept is still at its infancy, confirming that the proposal of a common and unambiguous definition, especially in manufacturing, is still yet to be proposed. In addition, evidence shows that DTw is still a misunderstood technology that is not yet fully explored, lacking a bidirectional link with the shopfloor that can only be overcome through combined use with other existing systems, such as the Manufacturing Execution System (MES) (Galli et al., 2023). According to this, with this paper we want to go beyond the general reviews found in literature and explore such technology from a more practical and conceptual perspective. Our purpose is to analyze and review the various framework and architecture of DTw in manufacturing that have been proposed, with a special focus on the interaction and synergy with other operation management tools such as the MES, as it is an essential element of the digital thread, both to channel shopfloor data and send manufacturing order to machines. By reviewing these proposals and taking into consideration the contribution given by the previous reviews, we aim to give a new

Communications of the ECMS, Volume 37, Issue 1,
Proceedings, ©ECMS Enrico Vicario, Romeo Bandinelli,
Virginia Fani, Michele Mastroianni (Editors) 2023
ISBN: 978-3-937436-80-7/978-3-937436-79-1 (CD) ISSN 2522-2414

perspective on the understanding of the DTw concept which has not yet been proposed in the literature. Looking for the gaps and limitations, we aim to identify existing frameworks describing DTw implementation or design.

LITERATURE REVIEW

Purpose of the review

In this section, our purpose is to develop a review regarding DTw frameworks that have been found in literature and proposed or adopted in the manufacturing field. Since there is no evidence of a standard framework for the DTw, but a large variety of proposals, our aim is to analyze them to highlight the differences and trying to find some important similarities. This will help us to identify some hypothetical clusters and resulting trends that could act as guidelines for the adoption of a specific framework in accordance with the purposes or technologies requirements. Indeed, trying to define some relevant clusters, we analyzed the papers according to specific features that have been recognized as fundamental in the manufacturing field. Particular attention was given to the application purposes of the DTw and its services, the technologies and software that have been integrated or used belong this tool, and the architecture defined for the framework itself. Taking (Cimino et al., 2019) literature review approach as a reference for our analysis, we extended its main analysed features to propose our updated review table. Considering newer papers found in literature since 2018, important elements for our purposes have been considered. Additional DTw services emerged in this review (“Scheduling” and “Layout optimization”) as illustrated in Table 1. Also the combination of DTw and new technologies within Smart Manufacturing have been studied (“MES”, “ERP”, “IoT”, “CPS”, “AI”) and reported in Table 2. Finally, we focus on DTw frameworks, proposing different architecture clusters.

Digital Twin Services

The first features that have been analysed refer to the “Application purpose” of the DTw, showing how this technology has been conceived and implemented for different scopes within the manufacturing field (see Table 1). Referring to the distinction introduced by (Cimino et al., 2019), only few of the features defined from the authors have been identified in the literature. The main purposes that we highlighted regard the “Support to the management of the production system”, by providing a support for decision-making operations and the management in general. Then, DTw can help to “Monitor and improve the production process”, monitoring the various parameters during production, integrating in some cases accurate algorithms or modules for optimizing it. Finally, evidence showed that DTw can be used to “Handle the flexibility” of the production systems and for “Maintenance” purposes. From the Table 1 we can see that the majority of the DTw are implemented to monitor and improve the

Authors	Application purposes				Digital twin services						
	Support to the management of the production system	Monitor and improve production process	Handle flexibility	Maintenance	Real time state monitoring	Failure analysis and prediction/ maintenance	Behaviour analysis for user operation guide	Analysis for optimization	Layout optimization	Energy consumption monitoring	Scheduling
Coronado et al., 2018		✓			✓	✓		✓			
Zhuang et al., 2018	✓	✓			✓	✓					
Cimino et al., 2019		✓			✓					✓	
Negri et al., 2020	✓	✓			✓	✓					✓
Villalonga et al., 2020	✓	✓		✓	✓			✓			✓
Ruppert et al., 2020		✓			✓						
Rocca et al., 2020	✓	✓			✓					✓	✓
Ward et al., 2021		✓			✓						
Martinez et al., 2021		✓			✓	✓					
Barbieri et al., 2021		✓			✓	✓		✓			✓
Negri et al., 2021	✓				✓	✓		✓			✓
Ragazzini et al., 2021		✓			✓			✓			✓
Villalonga et al., 2021	✓	✓			✓			✓			✓
Bárkányi et al., 2021		✓			✓			✓			
Wang et al., 2021		✓			✓	✓		✓			✓
Guo et al., 2021	✓	✓			✓			✓	✓		✓
Choi et al., 2022		✓			✓			✓			
Xin et al., 2022	✓			✓	✓	✓		✓			
Novák et al., 2022	✓	✓			✓			✓			✓
Yang et al., 2022	✓	✓	✓		✓			✓	✓		
Eyring et al., 2022	✓	✓			✓	✓	✓				
Eunike et al., 2022	✓	✓			✓			✓			✓
Magalhães et al., 2022		✓			✓						
Li et al., 2023		✓			✓	✓		✓			✓

Table 1: Digital Twin application purposes and services review

production process, often combined with the purpose of supporting the management.

Going into more detail with the Digital Twin “services” features (see Table 1), also defined by (Cimino et al.,

2019), we focused on the typology of DTw services that are implemented or considered while developing the simulation purposes.
The services "Real time state monitoring", "Failure analysis and prediction/maintenance", "Behaviour analysis for user operation guide", "Analysis for optimization" and "Energy consumption monitoring" refer to those illustrated by (Cimino et al., 2019). Then, more features were discovered during the analysis. With the "Layout optimization" feature, we refer to the use of the DTw as a simulation environment to improve the layout configuration of a production line (Guo et al., 2021); (Yang et al., 2021). Finally, the "Scheduling" column aims to show the use of the DTw to fulfil a function that is inside the MES scope.
Indeed, evidence from the analysis has shown that there's an emerging wide use of the DTw for "scheduling" functions within the manufacturing field. This, demonstrates how the DTw is considered a key approach to enhance the system reactivity to uncertain events and provide a new solution for the optimization of production line system (Barbieri et al., 2021; Guo et al., 2021). According to (Villalonga et al., 2020), the scheduling and the global optimisation modules are responsible to carry out actions of reconfiguration and optimization based on the information collected from the global DTw, the MES, the performance indices and other parameters and variables defined by the operators. Indeed, DTw is able to integrate actual processing data and simulated data, while considering more comprehensive information to support the precise scheduling decisions (Li et al., 2023).
Finally, trying to identify some correlations between the DTw services and the application purposes, we can state that any clear or significant correlations have been highlighted.
The only relevant result is given by the common trend that the totality of the papers uses the DTw as a "Real time state monitoring" service, with no distinction to the application purpose. In this regard, we can assume that DTw is an incompletely exploited technology. In this sense, considering (Kritzinger et al., 2018) distinction, despite the numerous services that DTw can provide, the trend among manufacturing applications is a mere use of a Digital Shadow. Consequently, research for systems that can provide the required bidirectionality is necessary.

Technologies and Software Adopted

In this section we want to analyse the various DTw from a technical and practical point of view, giving a look to its interfaces to the real system, and trying to identify some similarities among the technologies that have been integrated or adopted alongside the DTw to ensure the interoperability and synergy required by the smart manufacturing. Firstly, according to (Cimino et al., 2019), some technical characteristics were analysed (see Table 2). Through the "Simulation features", we reported the "Software" used to create the simulation environment and the type of simulation "Model" implemented. Indeed, referring to (Kritzinger et al., 2018) distinction, a DTw is mainly based on a Digital Model (DM). In this sense, a proper analysis of these features is necessary. Regarding these, we can identify a trend which characterizes a wide use of a Discrete Event Simulation (DES) model to represent the production system.
Then, compared to (Cimino et al., 2019) review, we searched for additional evidence of interfaces with technologies and software that have been adopted belong to the DTw, highlighted by the "Technologies" columns.

Authors	Simulation features		Technologies					
	Software	Model	MES	ERP	ioT	CPS	Cloud	AI
Coronado et al., 2018	Android	Acquired data	✓			✓	✓	
Zhuang et al., 2018			✓	✓	✓			
Cimino et al., 2019	Matlab/Simulink		✓		✓			
Negri et al., 2020	Simulink		✓			✓		✓
Villalonga et al., 2020	MatLab/Simulink		✓		✓			✓
Ruppert et al., 2020	Plant Simulation	DES model	✓	✓				
Rocca et al., 2020	Simulink		✓			✓		
Ward et al., 2021	Plant Simulation	DES model			✓	✓		
Martinez et al., 2021			✓	✓	✓	✓		✓
Barbieri et al., 2021	Simulink	DES model	✓					✓
Negri et al., 2021	Matlab/Simulink	DES model						✓
Ragazzini et al., 2021	Simulink (SimEvents)	DES model						✓
Villalonga et al., 2021		DES model	✓		✓	✓	✓	✓
Bárkányi et al., 2021	Plant Simulation	DES model					✓	✓
Wang et al., 2021		3D model CAD/CAM	✓	✓				✓
Guo et al., 2021	Plant Simulation	DES model	✓		✓			✓
Choi et al., 2022		3D model (CAD, ..)	✓		✓	✓	✓	
Xin et al., 2022		DES model	✓			✓	✓	✓
Novák et al., 2022			✓	✓				✓
Yang et al., 2022	Plant Simulation	DES model	✓	✓				
Eyring et al., 2022	FlexSim	DES model						
Eunike et al., 2022							✓	✓
Magalhães et al., 2022	CIMSoft V 88-113D Amatrol tool		✓	✓		✓	✓	✓
Li et al., 2023	3DMAX; Unity							✓

Table 2: Digital Twin features and related technologies review

Among them, important evidence is represented by the "MES" feature, collecting papers referring to its theoretical or physical integration within DTw or its use alongside DTw. Results from the review show that the majority of the papers refer to the MES, demonstrating an important emerging trend in the manufacturing applications. Indeed, following the classification introduced by (Kritzinger et al., 2018), which defines a proper DTw when data flows between an existing physical object and a digital object are fully integrated in both directions, the MES is recognized by (Negri et al., 2020) as the system that can actually recreate a proper DTw. In this sense, the MES can guarantee the required bidirectionality between the digital and

physical world and appears as the ultimate support tool within a smart manufacturing.
In the remaining columns, attention was paid to the use of DTw combined with other technologies that have been considered influential in a I4.0 background. Among them, we reported the use of the Enterprise Resource planning "ERP", the Internet of Things "IoT", and the presence of an environment that had reached a Cyber Physical System "CPS" configuration. For the "cloud usage" aspect, we highlighted those papers that use a cloud or build a cloud-based DTw application. Lastly, the "AI" column refers to the presence of Artificial Intelligences (AI). In this feature we considered the use of proper AI technologies or the presence of "intelligence layers" or "intelligent algorithms" within the architecture of the DTw. Among them, (Barbieri et al., 2021) consider an intelligent layer, developed with Matlab, that receives information of a breakdown from the PLC, and the remaining jobs to be produced from the MES. Once the DTw has updated the plant status, and the Genetic algorithm has generated different production sequences, the DTw will test and calculate the time difference between the start and finish of a sequence of jobs or tasks for each one of them and the new optimal sequence will be sent to the MES. According to this, we tried to find some correlations between the application purposes introduced in the previous section and the technologies used along the DTw. However, no relevant results have been identified.
Finally, a general result can state that the DTw never comes as a stand-alone technology. Indeed, evidence from the Table 2 proves that, in the manufacturing field, there's a trending effort to provide a higher degree of integration among such tools.

Architectures

In this last section we want to analyse the DTw from a new perspective. Our purpose is to identify similarities among the manufacturing DTw frameworks found in the literature, focusing on the structure of the proposed architecture, and trying to find some correlations in terms of form and conceptualization. In this sense, we identified three hypothetical clusters which can represent the architectures found in the Table 3.
First, the "Traditional" column identifies a wide cluster grouping architectures that represent an evolution of the first DTw framework introduced by Grieves in 2002 (Grieves & Vickers, 2017), illustrating a basic representation of data flows between a real object and a virtual object. Among them, some frameworks reinterpret this structure, showing explicitly the (Kritzinger et al., 2018) distinction of a "Digital Shadow", a "Digital Model" and a full DTw (Cimino et al., 2019; Negri et al., 2020).
Therefore, in general, this cluster collects basic architectures where the DTw is in parallel with the real system, discussing interfaces and interoperability with operations management systems such as MES, ERP and optimization modules (Cimino et al., 2019; Magalhães et al., 2022). Looking at the result within this cluster, we can assume that (Barbieri et al., 2021; Negri et al., 2020; Novák & Vyskočil, 2022; Ragazzini et al., 2021) present similar architectures, revisited with the specific inclusion of optimization modules or intelligent layers. In particular, we can assume that (Barbieri et al., 2021; Novák & Vyskočil, 2022) propose the same architectures. In both cases the DTw is synchronized with the real production system through an MES, allowing optimization procedures that reflect the actual state of the system. The proposed architecture conforms Industry 4.0 design principles and fills the gap between Industry 4.0 components on the shop-floor level and the traditional ERP system level, managing production/customers' orders (Novák & Vyskočil, 2022).
Some authors proposed DTw concepts based on (Kritzinger et al., 2018), namely (Cimino et al., 2019; Negri et al., 2020). On the other hand, those referring to (Tao & Zhang, 2017) differ. Instead, they emphasize the presence of a shared database and a service-oriented instance.

Authors	**Traditional**	**Service Oriented**	**Fractal**
Zhuang et al., 2018		✓	
Cimino et al., 2019	✓		
Negri et al., 2020	✓		
Villalonga et al., 2020			✓
Ruppert et al., 2020	✓		
Martinez et al., 2021			✓
Barbieri et al., 2021	✓		
Negri et al., 2021	✓		
Ragazzini et al., 2021	✓		
Villalonga et al., 2021			✓
Wang et al., 2021		✓	
Xin et al., 2022			✓
Novák et al., 2022	✓		
Yang et al., 2022	✓		
Eunike et al., 2022	✓		
Magalhães et al., 2022	✓		
Li et al., 2023		✓	

Table 3: Digital Twin architectures clusters review

Thus, the second cluster concerns the adoption of the architecture of the Digital Twin for the Shop-floor (DTS), introduced by (Tao & Zhang, 2017). Its evidence is shown in the "Service Oriented" column. The DTS architecture consists of four components. A Physical Shop-floor (PS) that includes a series of entities existing objectively in physical space. A Virtual Shop-floor (VS) that consists of models built in multiple dimensions. A Shop-floor Service System (SSS) that represents an integrated service platform, encapsulating functions of information systems, computer aided tools, models and algorithms. Finally, the Shop-floor Digital Twin Data (SDTD) that includes PS data, VS data and SSS data, as well as the existing methods for modelling, optimizing and predicting. (Tao & Zhang, 2017).

Three articles refers to this specific architecture (Li et al., 2023; Wang et al., 2021; Zhuang et al., 2018), adapting it to their specific scenario and improving it with a specific intelligent algorithm in one evidence. Indeed, (Li et al., 2023) considers a real-time optimization strategy of scheduling scheme based on rolling window mechanism and grey wolf optimization algorithm that are encapsulated into the job shop service system to drive the service composition and the subsequent scheduling processes.
However, the relevant element introduced in this shared architecture is the big data storage and management platform that is the driving force and foundation in a smart production management and control system (Zhuang et al., 2018).
The last cluster is illustrated by the "Fractal" column, showing DTw containing local or specialized DTw. Among them, (Villalonga et al., 2020) defines a DTw that can be classified into three main detail levels: local, system and global, according to the system that it represents. At the local level, DTw represent the dynamics of the equipment pieces that compose the different production systems. At system level, the interaction between the equipment pieces that make up a production line. Finally, at global they replicate the behavior of the entire shop floor production. Depending on the DTw level, different actions can be carried out aimed to optimize the production, perform predictive maintenance, scheduling, reconfiguration and, decision making to assist the operators. Its structure is centred on promoting local decision-making through the DTw module.
Finally, we searched for correlations between the application purposes and the architecture adopted in the specific case, trying to discover if the objective of the application could influence the architecture of the DTw proposal. Despite the definition of clusters have helped to identify some recurrent features adopted by different authors, no relevant correlations to their purposes have been identified. However, evidence of integration of tools such as the MES in some architecture provides further demonstration of the level of synergy that should exist between this technology and the DTw, enabling the required bidirectionality.

Findings of the Review

To summarise the results obtained from the review tables, we can confirm that DTw is used over disparate applications within the manufacturing. However, despite the various services that DTw can offer, we have observed that it is mainly conceived as a unidirectional tool to monitor the status of the equipment in real time.
Anyway, searching for interfaces with technologies and systems that could guarantee the DTw services, we highlighted an emerging effort to provide the synergy and bidirectionality with the real system required for the Smart Manufacturing. In particular, several references to the integration or conceptualization of the MES were highlighted. Indeed, the MES appears as a necessary system to enable DTw functions. In this regard, we noted an emerging trend in the use of such technology for scheduling services, whose evidence results in an additional feature compared to those identified by (Cimino et al., 2019). Another trend that emerged from the review is the use of AI, which seems a growing field within the Smart Manufacturing. However, searching for correlations between the application purposes and the different features highlighted in the review tables, we can state that no relevant trends could be identified.
In addition, only 2 of the purposes defined by (Cimino et al., 2019) have been largely adopted, resulting in an combination them in many cases. Since the DTw can be implemented for various purposes within a manufacturing, the use of specific technologies or functions cannot be confined to a single application.

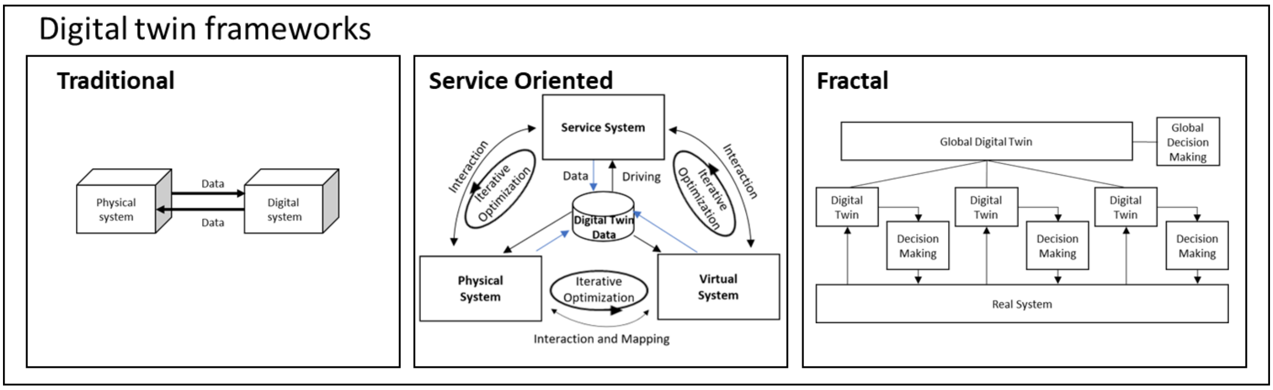

Figure 1: Architecture clusters identified in the review

Finally, an important contribution of the review concerns the similarities found among the various DTw architectures, resulting in the definition of three clusters. For each of them, a reference framework that generalize the common features is provided (Figure 1). For the "Traditional" cluster, an adaptation from the framework of (Grieves & Vickers, 2017) is proposed. The physical and digital systems present a parallel connection and, according to (Kritzinger et al., 2018), the data flows between the two systems should be fully integrated. For the "Service Oriented" cluster, we can observe a generalization of the architecture introduced by (Tao & Zhang, 2017), where the presence of the three components, the common data base and their connections is highlighted. Finally, for the "Fractal" cluster, we propose an adaptation from the architecture

defined by (Villalonga et al., 2020), whose redundancy comprehensively illustrates the features of the cluster.
However, even in this case no correlations with the application purposes were found, but a resulting trend in the integration of the MES has been highlighted.

CONCLUSIONS

The review that we conducted has shown that DTw is still an ambiguous term. The results have demonstrated that DTw services, technologies used, and architectures are independent: we could not find any correlation architecture, technologies or DTw services.
However, some important trends have been identified:

- Scheduling is a promising area of application for manufacturing.
- MES and AI are two emerging tools within DTw development.
- DTw with similar application purposes can be described with different architectures.

In accordance with these, future research should focus on the definition of more accurate application purposes, in order to consider the adaptability and versatility of the DTw over different scopes. This could facilitate the identification of further correlations with the different features that the DTw can implement. In particular, a correlation between specific application purposes and the architecture clusters that we have identified should be provided. In this sense a guideline could be defined to support implementation, and the proposed frameworks could serve as a basic architecture the designer can refer to, adapting it to the specific scenarios and requirements. Lastly, taking the identified trends into account, any proposed architecture should include the MES, as it is recognized as an essential element of the digital thread.

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