The International Journal of Advanced Manufacturing Technology (2023) 126:875–889
https://doi.org/10.1007/s00170-023-10902-7

CRITICAL REVIEW

Integrating the digital twin concept into the evaluation of reconfigurable manufacturing systems (RMS): literature review and research trend

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Received: 26 August 2022 / Accepted: 14 January 2023 / Published online: 7 March 2023

Abstract

With the rapid advent of new information technologies (Big Data analytics, cyber-physical systems, such as IoT, cloud computing and artificial intelligence), digital twins are being used more and more in smart manufacturing. Despite the fact that their use in industry has attracted the attention of many practitioners and researchers, there is still a need for an integrated and comprehensive digital twin framework for reconfigurable manufacturing systems. To close this research gap, we present evidence from a systematic literature review, including 76 papers from high-quality journals. This paper presents the current research trends on evaluation and the digital twin in reconfigurable manufacturing systems, highlighting application areas and key methodologies and tools. The originality of this paper lies in its proposal of interesting avenues for future research on the integration of the digital twin in the evaluation of RMS. The benefits of digital twins are multiple such as evaluation of current and future capabilities of an RMS during its life cycle, early discovery of system performance deficiencies and production optimization. The idea is to implement a digital twin that links the virtual and physical environments.
Finally, important issues and emerging trends in the literature are highlighted to encourage researchers and practitioners to develop studies in this area that are strongly related to the Industry 4.0 environment.

Keywords Reconfigurable manufacturing system (RMS) · Industry 4.0 · Systematic literature review (SLR) · Digital twin (DT) · Reconfigurability evaluation

1 Introduction

Faced with a global COVID-19 crisis and a shortage of electronic components, companies that design complex products must collaborate in ad hoc networks. Redesigning a network requires a clear understanding of the market positioning of the current product portfolio, customer requirements, and the maturity of products and processes. Globalization poses new challenges for manufacturers: unpredictable market changes, rapid variations in demand, and frequent new product introductions. In these circumstances, the demand for a rapid response to these changes has been proposed.

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Reconfigurability is a capability that allows manufacturing systems to add, remove, and rearrange components to satisfy rapidly changing markets. Zhang et al. [65] defined a reconfigurable manufacturing system as derived from modular core processes, both software and hardware, that can be rearranged or replaced quickly and easily. Several attributes of production system reconfigurability can be found in the literature, but most of them confirm that one can narrow down six key or fundamental characteristics. These characteristics can be divided into two types: core characteristics that are customizability, convertibility, and scalability that reduce the cost of reconfiguration, and supporting characteristics that are modularity, integrability, and diagnostics that reduce reconfiguration time according to Koren and Shpitalni [31]. Modularity in manufacturing systems implies that all the system's components, both software and hardware, are designed to be modular [31]. Integrability is the ability to readily join modules and future technologies [42]. Diagnosability is the capacity to diagnose the causes of bad quality products rapidly after a reconfiguration process [31]. Adaptability provides an adjustable structure for the manufacturing system to accommodate its capacity and functionality to new production requirements [39]. Customization allows the adaptation of a system's configuration to produce the product families required [52]. Koren et al. [33] proposed a reconfigurable manufacturing system (RMS), indicating that DT is an effective way to overcome the complexity of the system, and established the requirement of the effectiveness of the developed strategy/algorithm that can be employed in real time. Based on the RMS, Zhang et al. [68] presented a reconfigured DT model based on a five-dimensional reconfigured DT model, namely geometry, physics, capacity, behavior, and rules. The reconfiguration strategy is based on a dependency tree. Zhang et al. [65] proposed a reconfigurable DT manufacturing system and reconfigurable strategies for different levels of the manufacturing system, from equipment level to service level.

Despite increased practical interest, the research remains silent on the integration of the digital twin into RMS. The objective is to highlight the main research streams, application areas and methodologies that support the design and evaluation of RMS. This research aims to answer the following questions: Firstly, what is the existing work and what are the current research trends on evaluation and the digital twin in reconfigurable manufacturing systems? Secondly, what are the existing research gaps and what are the potential contributions for future work? The rest of this paper is organized as follows: the second section presents the methodology of the review. A descriptive analysis of the selected articles is contained in the third section. The fourth section categorizes and discusses in detail the existing work according to categorization criteria. Research trends and gaps are discussed in the fifth section. The sixth section aims to identify some directions for future research. Finally, the seventh section is the conclusion.

2 Research methodology

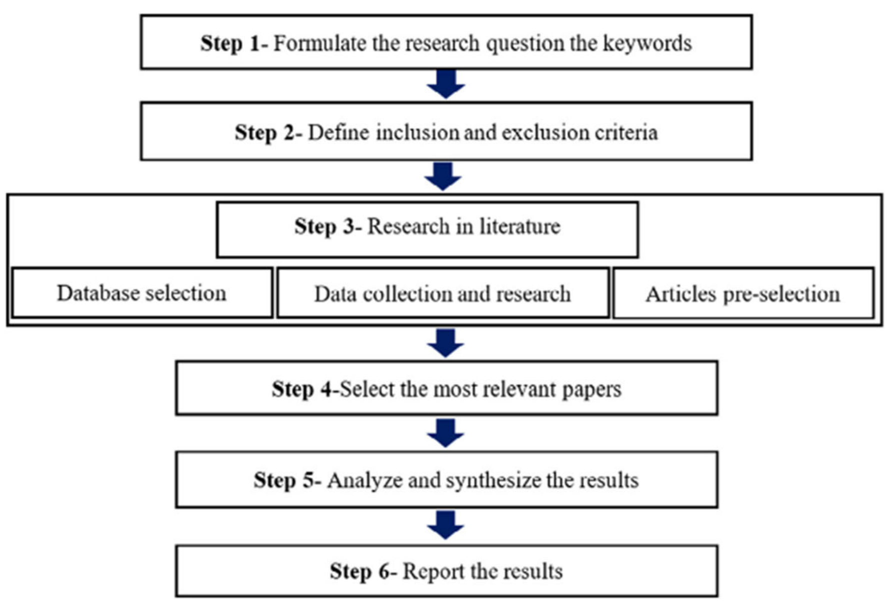
To answer the research questions identified in the previous section, a SLR is conducted in order to provide a detailed and comprehensive analysis of the state of the art. In this study, the guidelines proposed by Durach et al. [9] to conduct a SLR have been used. The methodology of this study consists of six steps (see Fig. 1):

i) Formulation of the search question and choice of keywords,
ii) Definition of inclusion and extrusion criteria,
iii) Search in databases,
iv) Papers selection, discussion and analysis of the results, and
v) Reporting of the results.

2.1 Question formulation and keywords

The first step in an systematic literature review (SLR) is to clearly define one or more research questions. In this sense, the main topic of our research is to examine the current state of the art dealing with digital twin in the evaluation of reconfigurable manufacturing systems. Furthermore, depending on the research objective, it is necessary to define a list of keywords in order to localize and limit this study.

Fig. 1 Six-step Research Methodology



The main keywords are as follows: "RMS evaluation", "Digital twin and RMS" and "Measurement or RMS and Digital Twin".

2.2 Inclusion/exclusion criteria

In addition to the keywords defined previously in the first step, a list of inclusion and exclusion criteria was established to limit the literature search and to select the articles that we would focus on. The set of criteria developed in this search is presented in Table 1.

2.3 Data search

In this step, we have defined three sub-steps: The first concerns the selection of databases. Consequently, we have selected the following source databases: Google Scholar, Web of Science, Scopus, Taylors Francis, Springer, Science Direct and Wiley Online Library. We then commenced a data search of the various databases identified by combining the keywords defined in the first step, for example, "RMS evaluation ", "Digital twin - RMS", in combination with "RMS measurement-digital twin". In the literature search phase, we identified a first set of articles based on the relevance of the title according to the context of the study. A total of 76 articles were identified in this phase.

2.4 Selection of the most relevant papers

To reduce the size of the database constructed in the previous step and to review a reasonable number of studies, we applied a filter using the inclusion/exclusion criteria. This step aims to identify the most relevant studies to focus on and eliminate irrelevant studies from our study. During the selection phase, we read the full text of each article and reviewed the list of references for each. In addition, we identified key authors contributing to reconfigurable production systems to perform a second search based on their names. Next, we added articles that were not initially found in our database studies.

2.5 Analysis, synthesis and results reporting: classification methodology

Once the relevant papers have been identified, steps (5) and (6) aim to synthesize the literature and to report the results. Firstly, a descriptive analysis of the identified literature was conducted according to the distribution of the work in the different journals and over time. Then, based on the research questions presented in the first section, the articles were classified according to the decision problem addressed. In addition, the reviewed studies were classified according to the research methodology used. Articles that used mathematical models were classified as quantitative approaches. The second subcategory, called qualitative approaches, contains exploratory research that focuses on case studies or interviews with practitioners to identify the challenges of assessing the reconfigurability of RMS in companies. The last approach contains analyses on the digital twin in RMS. In the following sections, we have conducted an in-depth analysis of the literature identified according to the above categorization criteria. This categorization allows us to determine the current trend in the evaluation of RMS reconfigurability and digital twin in enterprises and to identify the research gaps in this area.

3 Categorization analysis

In the section, a literature review was prepared. This includes different types of work. In order to do this, we have brought together all the papers dealing with this subject in order to study the existing situation. We also proceeded by classifying the papers according to the criterion "type

Table 1 Inclusion and exclusion criteria used to select papers

	Criteria	Justification
Inclusion	Papers published between 2010 and the first half of 2022	Focus on the most recent publication recent publication
	Publications in peer-reviewed journals and conference papers	Articles related to the evaluation of RMS and the digital twin - RMS.
	Empirical and experimental studies and review articles	research approaches research approaches
Exclusion	Documents related to the design of RMS	The purpose of the research is to review the existing literature.
	Studies in a language other than English and French	The researchers involved in this project can read these languages

of proposal" which gave two groups: papers proposing approaches to evaluate RMS and digital twin approaches.

3.1 Approach to the evaluation of RMS

Gumasta et al. [19] have worked on mastering reconfigurability, which requires the evaluation of its characteristics. The contribution by Gumasta et al. [19] presents assessments obtained through mathematical formulae and qualitative observations and then brought together via the MAUT (multi-attribute utility theory) to give a measure of the reconfigurability of RMS. This work can be extended to take into account handling equipment, tool attachments, layout, etc., and can be extended to take into account the use of the MAUT. Farid [11] has worked on the evaluation of reconfigurability and its characteristics (modularity, integrability, customization and convertibility) via axiomatic models and degrees of freedom. Reconfigurability was evaluated by the sum of the integrability and convertibility of the system. In this contribution, Farid [11] evaluated the reconfigurability based on the characteristics as well as the production data (processes, workstations ...). This contribution is limited to evaluating the system's capacity to perform changes in functionalities but does not take into account changes in relation to production capacity and batch sizes (scalability). Napoleone et al. [45] defined reconfigurability of production systems as a capability that companies must master in order to survive and remain competitive in the market with products whose life cycle is getting shorter and shorter and fluctuating demand. Thus, these two papers first aim at analyzing this capability, breaking it down into key characteristics. Secondly, the authors analyze the characteristics in order to determine the existing relationships between them and to highlight the external elements likely to have an impact on them. This model is a first step in the construction of a tool for assessing reconfigurability in terms of characteristics and the relationships between them. Maganha et al. [39] conducted a study on a panel of about 100 Portuguese companies. For this purpose, they developed a questionnaire with closed questions, evaluated on a Likert scale, structured around the characteristics of reconfigurability. The answers provided an overview of the level of implementation of the reconfigurability characteristics in these companies. In this way, it is possible to have a qualitative overview of the level of reconfigurability of the production lines. Through interviews constructed from questionnaires, Andersen et al. [2] constructed a methodology for designing the RMS that relies on company participation. The method was applied to two Danish companies, with whom regular meetings were held in order to conduct the study. Reconfigurability requirements and limitations in terms of line reconfigurability are identified. These two approaches, based on questionnaires, do not provide a precise objective measure for comparing different production systems. However, the questionnaires developed by Maganha et al. [39] and Andersen et al. [2] can be used for "field reconnaissance" in terms of reconfigurability. These qualitative analyses can be used to discover and make an initial analysis of a facility to be studied, before moving on to an evaluation using quantitative indicators. Rösiö et al. [53] propose to evaluate the characteristics of reconfigurability on a scale of four values between 0 and 1, by qualitative judgment of 10 people active in industrialization. For each criterion, a literature search allows to define the associated sub-criteria as well as the parameters having an impact on this criterion. Then, during interviews, the interviewees are asked to evaluate the characteristics of the reconfigurability of the existing system in the company. The different levels of reconfigurability distinguished are the following: no possibility to increase the level of reconfigurability, possibility to increase the level of the criterion with a maximum effort, possibility to improve the criterion with little effort, and finally high level of reconfigurability not requiring any improvement on this criterion. The results obtained are approximate but allow us to draw a first outline of the effort required to make the line reconfigurable.

Like Rösiö et al. [53], Wang et al. [58] define a method for calculating the six characteristics of reconfigurability defined by Koren et al. [32]. Based on the number of modules in the system, the time required to switch from one configuration to another, the range of variability covered, and other factors, Wang et al. [58] present a model to numerically evaluate the customizability, scalability, convertibility, modularity, integrability, and diagnostic capability of a machining line. Their method gives quantitative values, which are more precise than the qualitative evaluation performed by Rösiö et al. [53]. Based on the availability of machines, Fragapane et al. [12] define the flexibility of the production system as the quotient of a magnitude related to the availability of each machine, taking into account the reconfiguration time, and a magnitude related to the availability of the whole production line considering the reconfiguration time. The higher the index, the more flexible the line is. This indicator allows them to confirm the increase of the reconfigurability of a production system by integrating mobile robotic resources. In contrast, there are other models for assessing RMS that have used measures other than reconfiguration characteristics. Goyal [17] proposed three indicators for the problem of selecting the best configuration for a machine in RMS, namely cost, operational capability and machine reconfigurability. In the context of selecting the best configuration in RMS, Mittal et al. [44] proposed performance indicators to ensure a responsive reconfigurable manufacturing system based on cost, reliability, usability and quality. In the same context, Gupta et al. [21] presented a set of indicators such as the following: convertibility, scalability, productivity and cost for the selection of the best configuration as well as the type of machine and its specifications, which ensures effective and efficient production. In designing the RMS, Goyal et al. [16] considered performance indicators such as cost, machine utilization, configuration convertibility and operational capacity to optimize the design of reconfigurable production lines. Delorme et al. [8] addressed the problem of balancing transfer lines in RMS. They considered two criteria to evaluate the performance of RMS, namely total cost and cycle time. Dahane and Benyoucef [7] proposed a new performance indicator to measure the effort of reconfigurability in RMS based on two functions:

i) The first function maximizes the reconfiguration index based on overall capacity;
ii) The second function allows to minimize the total cost.

Recently, Prasad and Jayswal [47] have developed a methodology to facilitate the design of RMS by including the calculation of the similarity matrix, the creation and selection of family shares based on three criteria which are as follows: reconfiguration effort, user cost and surface cost. The work of Huettemann et al. [24] also proposes quantitative criteria for evaluating the reconfigurable system. His approach, however, corresponds more to performance criteria than to transformation capacity criteria with regard to resources at the workstation level, and organization at the segment and line levels. In fact, the criteria correspond to resource utilization rates and production rates. For the other categories, the criteria mentioned can be used to account for the flexibility or reconfigurability of the system: type of technical solution for the transfer system and type of pallet for the product, method of supplying the line, process divisibility, traceability, etc. These indicators make it possible to evaluate the reconfigurability according to the level of production considered. Kapitanov et al. [29] measure the efficiency of the RMS through the performance of the production system. For this purpose, they define the level of potential flexibility of the system as the diversity of reactions of the RMS divided by the resource utilization time; and the level of flexibility as the actual level of variability of the system versus the lead time. The authors also define an indicator referring to the time of change between two configurations. However, the article does not present a concrete application of the indicators to a use case, which makes their reuse difficult. Beauville dit Eynaud et al. [10] carried out this empirical work in order to study reconfigurability within an automobile industry. This project aims, on the one hand, at highlighting the requirements of reconfigurability, its levers and limits within the company and, on the other hand, to weigh the six key characteristics of reconfigurability. The validity of this work is limited to the company in which the study took place and the results are subjective. It is necessary to vary the sectors and repeat this study in several other companies in order to generalize the results and make them objective.

This section has presented various reconfigurability indicators to assist in the design and tuning of reconfigurable production systems. Table 2 summarizes the indicators mentioned above and classifies them according to their qualitative, quantitative, performance or reconfigurability indicators, and their applicability to the evaluation of RMS. We have seen previously that qualitative indicators lack precision in the context of an approach aimed at industry. Concerning the quantitative reconfigurability indicators based on performance, the analysis of the bibliography has allowed us to identify precise and easily calculable indicators. However, the choice of measuring the reconfigurability of a system through its performance is questionable.

The challenges in assessing the level of reconfigurability involve mapping the attributes of the production system, outside the boundaries of the workstation, and adopting more rigorous analytical measures (see Table 3). It is clear from this Table 3 that there is no work on the integration of digital twins in the evaluation of RMS. To this end, accurate and quantitative reconfigurability indices are still lacking to account for the effects of handling devices, tools, and fixtures in the manufacturing environment, even for multiple demand scenarios, multiple period planning horizons, and multiple part manufacturing lines [15, 19].

3.2 Digital Twin approaches-RMS

The Industry 4.0 paradigm has been introduced for smart manufacturing with the virtual factory concept. The new concept for smart manufacturing is the digital twin. It enables the modeling of product life cycle operations. Products are developed and tested in a virtual environment [51]. The author further defines DT as "the digital representation of a unique asset (product, machine, service, product service system or other intangible asset), that alters its properties, condition and behavior by means of models, information and data." In other words, DT creates virtual models to simulate the functionality of the physical objects. The sensor system provides the DT with data regarding the physical objects [1, 26]. Hence, DTs analyze, predict, and simulate various changes to get implications of the physical entities' correspondence and in that way achieve optimization throughout the whole production line and supply chain [28, 48]. Grieves [18] defined the digital twin as a set of virtual information constructs that fully describes a potential or actual physical

Table 2 Classification and criteria of the approaches to reconfigurability in RMS

Reference	Type		Reconfiguration level			Indicators						
	Quantitative	Qualitative	Workstation	Factory	System	Features						Other indicators
						M	C	I	D	E	P	
Gumasta et al. [19]	✓				✓	✓	✓		✓	✓		
Goyal et al. [16]	✓		✓									(Cost, Operational, capability machine reconfigurability)
Farid [11]	✓		✓			✓	✓	✓			✓	
Mittal et al. [44]	✓		✓									(Cost, reliability, use, quality)
Goyal and Jain [15]	✓			✓			✓					(Cost, operating capacity, machine utilization rate)
Delorme et al. [8]	✓			✓								(Total cost and cycle time)
Haddou-Benderbal et al. [22]	✓		✓									(Total cost, reconfigurability index)
Wang et al. [58]	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	
Napoleone et al. [45]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Maganha et al. [40]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	(Convertibility + scalability = adaptability)
Rösiö et al.[53]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Beauville dit Eynaud et al. [10]	✓				✓	✓	✓		✓	✓	✓	
Prasad and Jayswal [47]	✓		✓									
Kapitanov et al. [29]	✓		✓	✓								(Time, flexibility)
Huettemann et al. [24]	✓		✓		✓							
Fragapane et al. [12]	✓			✓	✓							
Napoleone et al. [45]	✓			✓			✓					
Andersen et al. [2]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Maganha et al. [39]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Maganha et al. [40]		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	

Table 3 Reconfigurability indicators comparison

Référence	qualitative	quantitative	based performance	based on reconfiguration criteria	RMS	DT
Maganha et al. [39]	✓		✓		✓	
Andersen et al. [2]	✓		✓		✓	
Huettemann et al. [24]	✓	✓	✓		✓	
Rösiö et al. [53]	✓			✓	✓	
Gumasta et al. [19]		✓	✓		✓	
Farid [11]		✓	✓		✓	
Kapitanov et al. [29]		✓	✓		✓	
Fragapane et al. [12]		✓	✓			
Mittal et al. [44]		✓			✓	
Wang et al. [58]		✓		✓	✓	
Beauville dit Eynaud et al. [10]		✓	✓	✓	✓	
Napoleone et al. [45]	✓		✓	✓	✓	

manufactured product, from the micro-atomic to the macro-geometric level. In its optimal form, any information that could be obtained by inspection of a physical manufactured product can be extracted from its digital twin. The first DT model proposed by Grieves [18] consists of three elements: the physical product, the virtual product and their connection. The virtual product contains not only geometric information but also behavioral characteristics that show the performance of the system in response to external hazards. Based on the original 3D DT model, Qi et al. [49] and Tao et al. [55] proposed a five-dimensional DT model for shop-floor design, including physical entities, virtual models, services, data DT connections. Today, in the design of production systems, the most important attributes are flexibility, responsiveness, cost effectiveness and the ability to be easily reconfigurable. Therefore, DT can be divided into entity DT and scenario DT, as shown in Fig. 2. According to the 5-dimension model, as shown in Fig. 3, a variety of enabling technologies are required to support different modules of DT (i.e., physical entity, virtual model, DT data, smart service, and connection). For the physical entity, the full understanding for the physical world is a prerequisite for DT.

Zhang et al. [66] have proposed an approach for automatic reconfiguration of RMS through Digital Twin based modeling. The Digital Twin reconfigurable system is driven by a five-dimensional model. By mapping physical and virtual entities, they can infer capabilities and dependencies of the digital twin. The objective was to meet the requirements of different granularities and targets in terms of reconfigurability. In the same context, Benderbal et al. [4] provided a conceptual modular RMS-DT framework as a way to integrate the Digital Twin into the RMS. In fact, the Digital Twin framework aims at providing a holistic system visibility and a flexible decision making process to achieve the necessary responsiveness of the reconfigurable manufacturing system and improve its performance during its operation phase by continuously collecting real-time data from its components. Then, this data can be stored, processed and analyzed using information analysis as well as simulation and optimization module blocks. Based on the above ideas, Digital Twins can quickly provide critical decisions, such as the appropriate configuration of the reconfigurable manufacturing system, in order to effectively deal with sudden changes in a globally competitive market. Xu et al. [61] have offered a special issue on smart and resilient manufacturing in the wake of COVID-19. The authors proposed technical aspects of a manufacturing system with technology solutions that can help deal with the pandemic as we know it today and make them agile and resilient in the event of a similar event. Zhang et al. [67] proposed a resilience dynamics modeling and control approach for an electronic assembly

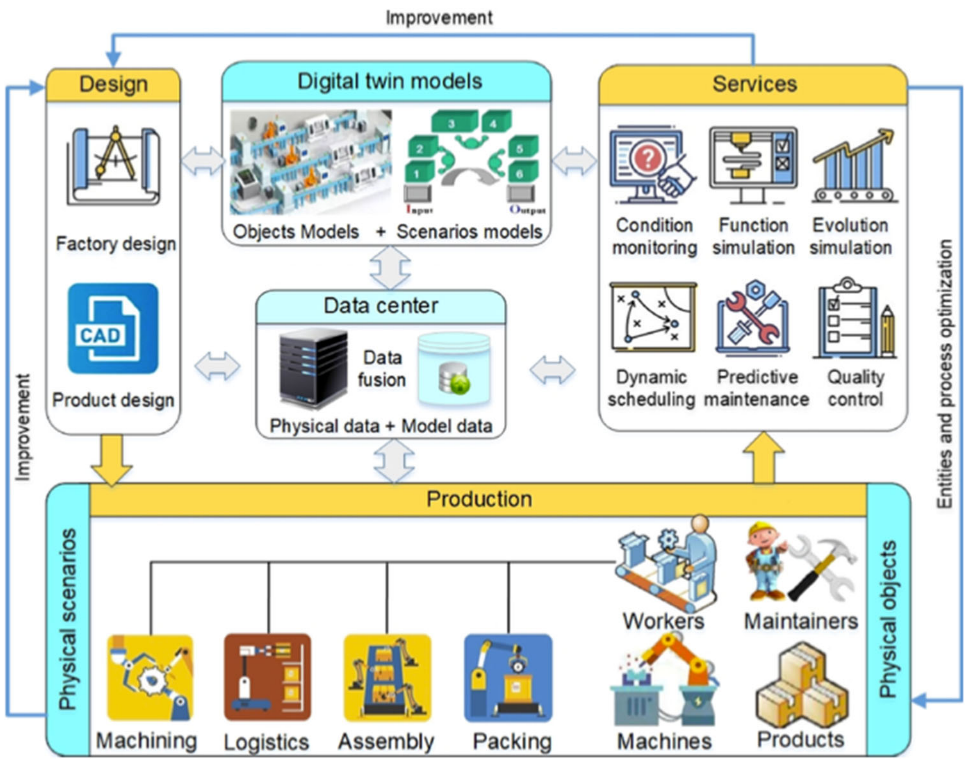


Fig. 2 Composition and application of digital twin [48]

line reconfigurable under disturbances. A Digital Twin (DT) platform is developed as a basis for resilience analysis, and open reconfigurable architectures (ORAs) are introduced to support the reconfiguration of the assembly line. In terms of reconfiguration, Leng et al. [34] proposed a new approach based on Digital Twins for a fast reconfiguration of automated manufacturing systems and a fast optimization process. The Digital Twin consists of two parts: the semi-physical simulation that maps the system data and provides input data to the second part, which is the optimization.

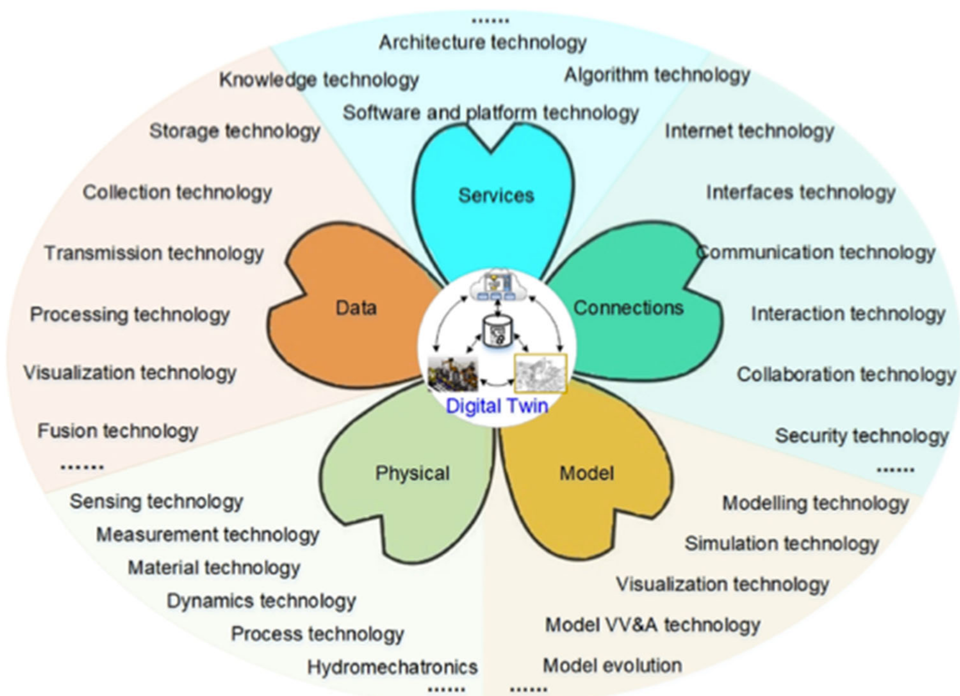


Fig. 3 Framework of enabling technologies for digital twin [48]

The results of the optimization part are sent back to the semi-physical simulation for verification. The proposed approach allows for rapid changes in manufacturing system capacity and the rapid integration of multiple processes into existing systems, enabling manufacturers to quickly launch new product orders. Related research and the application of the Digital Twin to product lifecycle management was presented in the papers by Yang and Li [63]. Zheng et al. [69] presented a broad and narrow definition of the concept and characteristics of Digital Twins. Based on the mentioned definitions, the authors introduced a Digital Twin framework for product life cycle management. This framework includes an information processing layer with three main functional modules, namely data storage, data processing and data mapping. Kombaya Touckia et al. [30] proposed a quick solution to the new configuration, providing compatible sequences of operation outputs. Subsequently, a simulation by the digital twin. They then applied these developments to an assembly process system. This model can also be deployed on other assembly systems that regularly need to be reconfigured quickly and efficiently. Therefore, the digital twin is also geared towards real-time, efficient and intelligent services and which fully integrates models, data and intelligent technologies to realize the virtual and real mapping and cross-domain interaction of data and models. The digital twin optimizes industry processes in various areas and enables the efficient and intelligent operation of a smart factory. Thus, digital twin technology is the key to the technology to realize a smart factory. Yi et al. [64] worked on a digital twin reference model for the design of an intelligent assembly process, which was applied to reality through experimental testing. Product manufacturing is the final stage of product development. Product manufacturing will benefit from the digital twin to increase manufacturing efficiency. Guo et al. [20] introduced a digital twin-based shop-floor modeling framework and conducted research with analyses on problems such as digital product definition, resource modeling, and digital process information definition. In the same direction, Zheng et al. [70] proposed a framework for applying digital twins in product life cycle management. Lu et al. [38] reviewed the recent development of digital twin technologies in manufacturing systems and processes, discussing the connotation, application scenarios, and research questions. Liu et al. [36] presented a digital twin-based methodology for rapid and individualized design of an automated flow-shop manufacturing system. Leng et al. [34] worked on the problem of individualization requests for the digital twin-based manufacturing system. Li et al. [35] studied the manufacturing resource recommendation method for the digital twin shop based on semantic modeling of manufacturing tasks. In addition, Wang et al. [59] discussed intelligent personalization based on digital twin data, which resulted in a new paradigm. Wei et al. [60] suggested a coherence conservation method for the digital twin of the CNC machine tool between the virtual space and the physical space. Li et al. [37] worked on a machining process monitoring method based on digital twins to help field operators monitor product quality in real time. Miao et al. [43] introduced the concept and reference architecture of the digital twin workshop. They studied fundamental problems, such as merging heterogeneous elements of a physical shop-floor, merging multi-dimensional models of a virtual shop-floor, merging physical and cyber data, and merging services of a shop-floor, thus providing a reference for companies to build a digital twin shop-floor. Miao et al. [43] analyzed the application of the digital twin in typical scenarios of development, manufacturing, maintenance, and other stages of the product life cycle. The above literature reveals that many researchers have conducted considerable research (see Table 4) and made progress in building the conceptual system and practice framework of digital twins.

The digital twin (DT) system framework is applied to various domains in the smart factory. The proposed work is based on the related work in the above literature, but further discusses the integration of DT in the evaluation of reconfigurable manufacturing systems, which complements the gaps in the existing literature on digital twins.

DT is an emerging technology with great potential. However, the following limitations hinder the growth of DT:

i) Most DT models contain only geometric models. Although some recent research has considered physical models, there is still a gap in behavior modeling and consumption modeling.
ii) Prolonged distortions occur during transmission. Current data transmission methods fail to meet the demand for high accuracy and high speed due to the large amount of data that must be transmitted simultaneously.
iii) Current data analysis algorithms and methods need to be improved in terms of both accuracy and speed.
iv) There are several DT platforms for different applications, especially in the areas of complex equipment monitoring and IoT.

Table 5 provides a concise summary of the different DT models or frameworks, their key components, references and criticisms.

4 Future research orientations

Many indicators on RMS evaluation [10, 11, 19, 58] (see Tables 2 and 3) are proposed in the literature, but there are no RMS evaluation indicators using digital twins

Table 4 Comparison of reconfigurability indicators based on digital twin

References	Design	Simulation	based performance	based on the reconf criteria.	RMS	I4.0-COVID-19
Yang and Li [63]	✓		✓		✓	
Grieves [18]	✓		✓		✓	
Zheng et al. [69]	✓		✓		✓	
Zhang et al. [66]	✓	✓	✓		✓	
Benderbal et al. [4]		✓		✓		
Leng et al. [34]	✓		✓		✓	
Koren et al. [33]	✓		✓	✓	✓	
Hashemi-Petroodi et al. [23]	✓		✓		✓	
Shao et al. [54]	✓		✓		✓	
Xu et al. [61]	✓		✓			
Kombaya Touckia et al. [30]	✓	✓	✓	✓	✓	
Ivanov and Dolgui [27]	✓	✓	✓			✓
Aheleroff et al. [1]	✓	✓	✓			
Qi et al. [48]	✓	✓	✓			
Kaivo-oja et al. [28]	✓	✓	✓			
Yi et al. [64]	✓	✓	✓			
Guo et al. [20]	✓	✓	✓			
Zheng et al. [70]	✓	✓	✓			
Lu et al. [38]	✓	✓	✓			

Table 4 (continued)

References	Design	Simulation	based performance	based on the reconf criteria.	RMS	I4.0-COVID-19
Liu et al. [36]	✓	✓	✓			
Leng et al. [34]	✓		✓	✓		
Li et al. [35]	✓		✓	✓		
Wang et al. [59]	✓	✓	✓			
Wei et al. [60]	✓	✓	✓			
Liu et al. [37]	✓		✓	✓		
Miao et al. [43]	✓	✓	✓			
Golgeci et al. [13]	✓	✓	✓			✓
Pournader et al. [46]	✓	✓	✓			✓
Govindan et al. [14]	✓	✓	✓			✓
Ivanov [25]	✓	✓	✓	✓		✓
Manuj and Mentzer [41]	✓	✓	✓			✓
Xu et al. [62]	✓	✓	✓			✓
Golgeci et al. [13]	✓	✓	✓			✓
Van Der Hoek et al. [57]	✓	✓	✓			✓
Chamola et al. [6]	✓	✓	✓			✓
Queiroz et al. [50]	✓	✓	✓			✓
Belhadi et al. [3]	✓	✓	✓			✓
Burgos and Ivanov [5]	✓	✓	✓			✓

Table 5 Summary of different DT models

References	DT models	Key components	Criticisms
Grieves [18]	Original DT	Physical products, virtual products, Physical products, virtual products, and connection between physical and virtual products Physical products, virtual products	Most contain only geometrical models.
Qi et al. [49]	Five-dimensional DT model	Physical entities, virtual models, services, DT data, and connections	Most contain only geometrical models, Lack of model in modeling behavior and consumption
Tao et al. [55]	Digital twin shop-floor	Physical shop-floor, virtual shop-floor, shop-floor, services, shop-floor DT data, and connection	
Zheng et al. [68]	Product manufacturing digital	Product definition model, geometric and shape model, geometric and shape model, manufacturing attribute model, behavior and rule model, and data fusion model	Contain only geometrical models
Zhang et al. [65]	Reconfigurable digital twin	Physical layer, model layer, data layer and service layer	Prolonged distortions occur during transmission
Tao et al. [56]	Digital twin driven product design framework	Planning and task clarification, conceptual design, embodiment design, detail design, virtual design, virtual verification	Prolonged distortions occur during transmission
Kombaya Touckia et al. [30]	Digital twin enabled Reconfigurable digital twin fault diagnosis framework and Reconfigurable digital twin	Physique system, enabling technology, DT model and predictive maintenance	Improvement of its algorithm for better accuracy and speed

(see Table 4) for accurate evaluation and use of real-time data using artificial intelligence. Faced with the increasing complexity of the structure of reconfigurable production systems, scientific research has turned to the use of intelligent monitoring techniques. Machine learning algorithms (classification algorithms) present a complementary alternative to traditional methods because of their ability to:

i) automate diagnostic and monitoring processes,
ii) disclose a maximum amount of information from a set of collected data (the progression of indicators over time, rapid reconfigurations, etc.),
iii) facilitate access to information, thanks to a synthetic and understandable presentation of the data,
iv) be configured to process the flow of information in real time.

To overcome this drawback, we propose to introduce the concept of digital twins in the evaluation of reconfigurable production systems. A digital twin, like a virtual prototype, is a dynamic digital representation of a physical system. However, unlike a virtual prototype, a digital twin is a virtual instance of a physical system (twin) that is continuously updated with performance, maintenance, and health status data of the latter throughout the life cycle of the physical system. Despite the relatively comprehensive five-dimensional DT model, existing key technologies, and the applications of DT mentioned earlier, some technical issues (e.g., computational effort and data transmission rate) still hinder the development of DT. The main challenges of DT construction in RMS evaluation can be summarized by the following five aspects:

i) Depending on the objective of evaluating the diagnosability of RMS (fault detection, monitoring, localization and/or characterization), two types of machine learning algorithms are to be applied: supervised or unsupervised classification algorithms. Supervised learning algorithms rely on a set of labeled data to create a classification model, allowing the classification of new operating data. An unsupervised learning model, on the other hand, deals with unlabeled data that the algorithm tries to understand by extracting features itself. Unlike unsupervised classifiers, supervised classifiers provide data belonging to well-identified classes. Such a result allows, in the case of machine diagnostics, not only the detection of faults, but also the ability to determine its nature, location and even severity. However, supervised type classification algorithms are very sensitive to the quantity as well as the quality of the data used in the learning phase. This training data usually corresponds to the historical data of the machine operation. This limits the reliability of the diagnosis to machines with extensive operating history. In addition, the physically collected data is often limited by the acquisition conditions and the specific elements for which it was recorded.

ii) Data acquisition and processing. Data is another key driver of DT, which consists of multi-temporal, multi-dimensional, multi-source, and heterogeneous data. The entire data life cycle includes data collection, transmission, storage, processing, fusion, and visualization [56]. To solve these problems, we need to integrate sensors, computer vision, Internet, IoT, databases, data fusion, and other technologies. It is clear that the foundation of digital twin integration is the incorporation of data and information, which is a significant challenge for manufacturers. It is used/adapted by digital twin users according to their needs, even though it was originally developed for those needs. To ensure reliable and real-time simulation analysis results, we need to develop fast and highly accurate data analysis methods. All of this facilitates the evaluation of real-time RMS.

iii) Real-time bidirectional connection between virtual and real space. The virtual model obtains real-time data from the physical entities, and the results of the analysis are used to guide the physical entities in real time. Due to the large amount of data, network transmission delays, model analysis time, etc., it is difficult for DT to realize a real-time bidirectional connection. We also have to solve problems such as visualization and human-equipment interaction.

iv) Environmental coupling technologies. The current DT lacks association with the external environment. The mechanism explaining how a physical object interacts with the environment has not been fully incorporated into virtual models. Many research works have explored the mechanism by which physical entities interact with their environment in reality. However, there is still an urgent need for a corresponding numerical expression method, which will lead to efficient and accurate prediction in future DT.

v) The final possibility is to include sustainability. Sustainable manufacturing is becoming a critical issue in new manufacturing environments. However, few works have considered sustainability and performance evaluation as part of their established digital twin frameworks. Therefore, sustainable manufacturing driven by digital twins needs to be critically analyzed.

5 Conclusion

Since the DT concept was proposed in 2003, DT has attracted increasing attention from industry and academia. DT represents an advancement in digitization and has evolved from the original three-dimensional model to a five-dimensional model consisting of a physical object, a virtual model, DT services, DT data, and a connection. The majority of the DT literature focuses on the conceptual development of DT frameworks for a specific implementation domain. Therefore, this paper summarizes technologies for implementing RMS evaluation using DT. Based on these technologies, this article provides a comprehensive review from two perspectives: (1) RMS evaluation measures, and (2) applications in the DT domain. At the same time, this article mentions the shortcomings related to the absence of environmental factors in the DT model and discusses the six-dimensional DT model regarding the environment. In response to these shortcomings, future research directions for RMS evaluation using DT should focus on the following: (1) The development of a data format that contains all the information and has consistency with real-world data, including geometric, physical, behavioral, and rule information. (2) Optimization of algorithms to improve the speed and accuracy of the algorithms. (3) Development of methods for integrating different communication protocols and data communication interfaces with various services to develop a unified DT platform that will enable real-time evaluation of RMS.

Data Availability The authors confirm that the data and material supporting the findings of this work are available within the article. The raw data that support the findings of this study are available from the corresponding author, upon a reasonable request.

Declarations

Ethics approval The authors declare compliance with ethical standards.

Consent for publication The authors consent to publish.

Conflict of interest The authors declare no competing interests.

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