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Digital Twin Driven Intelligent Systems and Emerging Metaverse

Springer

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ISBN 978-981-99-0251-4 ISBN 978-981-99-0252-1 (eBook)
https://doi.org/10.1007/978-981-99-0252-1

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

The notion of digital twins represents a new stage in smart system development that has already shown to have a huge impact in recent years. This new topic has been made possible and accelerated by the developments and integration of various technologies such as the Internet of things, sensor technology, artificial intelligence, data science, and machine learning. As a result, a digital replica with rich representations of physical entities can be developed that maintains connectivity with the physical entity and enables living monitoring, control and simulations for intelligent decision-making. Rather than relying on direct observation and on-site manual tasks, digital twins provide remote control of processes based on (near) real-time digital information. This idea of a smart, connected digital replica offers innovative solutions to various problems in a broad range of application domains, including manufacturing, aerospace, smart farming, health care, and the automotive industry. Responsible innovations using digital twins can increase leverage and productivity and help create unprecedented value.

Clearly, the digital twin concept is not just a temporary hype but a long-term trend affecting an increasing number of application areas. The concept can be explained from a rationally sound, historical perspective and is part of the ongoing digital transformation process. However, despite its prevalence and growing popularity, there still seems to be a lack of understanding and consensus on the core concepts and implementation of digital twins in various application domain contexts. New concepts are validated, further developed and accepted through lessons learned from real case studies and experience in the practical context. Yet, while the digital twin concept has been proposed earlier in history, its application in a broader context is relatively new. Moreover, the number of applications reported on digital twins is limited to support further reflection on digital twin concepts and therefore help to learn from recent experience and increase understanding beyond the level of hype. Therefore, we need more insights into the diverse applications of digital twins concepts and reflect on the best practices for effective, responsible innovation. Of course, this is no easy task, given the multidisciplinary and interdisciplinary nature of digital twins. Developing digital twin-based systems requires a holistic systems engineering approach where multiple disciplines and often conflicting stakeholder concerns must be considered.

This book provides a timely and complementary contribution to current knowledge of digital twins, with valuable information on key concepts, concrete applications, and a vision for the future. I invite you to read this book and benefit from the valuable contributions reported in the separate chapters.

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Digital Twin Fundamentals

The Digital Twin Case in the Technological Transformation Process: Research Articles, Academic Collaborations, and Topics

Muhammet Damar and Güzin Özdağoğlu

1 Introduction

Technological developments that drive the world to the fourth industrial revolution create a significant competitive advantage for businesses that can keep up with these developments. Product and service producers who want to exist in this competition feel time pressure in new product development, product life cycles, and decision support processes. As a result of the opportunities provided by the technological transformations experienced, the medium or long-term waiting for the direct implementation of planning and designs and analysis of the results are no longer present. Much faster or rapid prototyping environments replaced these and real-time simulations years ago [2, 12, 16, 32, 44].

The primary source of these developments is the pairing technology that NASA developed and used many years ago. Bedding and mirrored technology create an exact virtual copy of a system, product, production, or service environment with the help of a sensor, artificial intelligence, Internet of things, machine learning, virtual and augmented reality, quantum computing, autonomous programming, and related technologies. It has become possible to create. Even if proposed at the beginning of the 2000s [24], it was 2010 when NASA defined this technology as the "digital twin" for the aeronautic sector [45], and this technology was highlighted as an essential component of the industrial revolution.

Digital twin has been more frequently related to systems engineering and, or specifically, to model-based system engineering. Like a virtual prototype, a digital twin is a dynamic digital representation of an existing system [39]. With the digital

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_1

twin technology, a mirror image of the physical world can be created in the virtual world so that analysis of decision processes, plans, product development, and customer experiences on the system, product, or service can be made instantly. With the advantage of the ability to run much more advanced analysis and optimization models, it is possible to design the most suitable product for the needs of the customer, come up with the best plans, and eliminate unwanted situations as soon as possible [1, 25]. For this purpose, various models have been developed to integrate the Internet of Things and the other technologies that Industry 4.0 has provided [30]. Cloud computing, artificial intelligence, machine learning, big data analytics, and cyber-physical systems are the prominent technologies needed to design digital twins. The most frequent application areas that utilize these technologies are smart manufacturing, automation, quality control, production control, uncertainty and analysis, risk assessment, supply chains, operation and maintenance, real-time monitoring, real-time simulation, product life cycle, control systems, manufacturing process, fault detection, cyber-physical system, product design, machine tools, maintenance, production system, manufacturing industries, additive manufacturing, production process, process control, computer-aided design, and optimization.

Since its launch, the source of the rapid developments in this technology is the positive exponential trend followed by research in this field. In addition to technological developments, widespread effects of the results of these studies, which examine the topic from many different perspectives, are revealed by the publications they present to the literature. In this regard, the purpose of this chapter is to present bibliometric research, including the basic statistics, network relationships, and topic structures of the portfolio of articles in the relevant literature on digital twin technology enhanced with advanced visuals. In this context, related text and network analytics approaches are used along with bibliometrics and scientometrics. The data sources of the analyses are the leading scientific databases Web of Science (WoS) and Scopus and thus the study focuses on research articles published between 2010 and 2021 (June). As a result of the analyses, many output dimensions are obtained, such as authors, co-authorship relationships, journals, citation relations, keyword networks, and prominent topics and publication metrics.

In comparison to other studies, the research design is unique. The research, for example, includes not only the related papers in the WoS or Scopus databases but in both. This study handles these databases and provides findings comparatively. Even though the dimensions, criteria, and analyses are comparable to the previous research, none of them covers most of these dimensions together.

Digital twin technology is an integral part of the fifth industrial revolution [15], where personalized designs, cognitive programming, and collaborative robots are expected to be forefront. In this context, the findings presented reflect the structure of the existing literature on digital twin technology from a holistic perspective and have the qualities to support researchers and practitioners in this field in their research processes and accelerate this process.

2 Related Work

The research paper portfolio, rapidly amassed in the literature within the notion of a digital twin, is summarized using various approaches and serves as a reference for future research on this topic. These studies provide information extraction from different datasets, criteria, details, and dimensions in light of methods such as review, systematic review, and bibliometrics.

Krüger and Borsato [32] implemented the ProKnow-C method on a bibliometric dataset to filter the papers for further analysis and then discussed the recent studies in digital manufacturing and digital twin after presenting the descriptive statistics about the related work. Jones et al. [31] conducted a systematic review to recall the digital twin concept and characterize it over critical processes and terminology, along with knowledge gaps in the broader area. Agostino et al. [2] presented bibliometric research to reveal the application of simulation models in production and logistic systems related to digital twins before introducing their conceptual model. Chinotaikul and Vinayavekhin [16] examined digital transformation as a business research subject. They identified guiding publications and utilized co-word network analysis to reveal the intellectual structure of the selected papers. Kumar et al. [33] evaluated the papers from Scopus to infer key insights such as publishing volume, co-authorship networks, citation analysis, demographic distributions, concept proposals, keywords, affiliations, journals, and funding information. Ciano et al. [17] clarified the importance of digital twin in realizing smart industrial systems by discussing its role in implementing real-time systems, integration of digital twin, and Industry 4.0 technologies. Ante [5] conducted bibliometric research to identify the impact of digital twin on smart manufacturing and Industry 4.0 and applied exploratory factor analyses to categorize the implementation areas. Agnusdei et al. [1] assessed digital twin-oriented engineering and computer science studies to identify research clusters and future trends and discussed the findings from safety issues.

As evidenced by the cited research, as the number of studies centered on the notion of the digital twin grows, publications from other domains, authors, analyses, and models begin to appear in the literature. Another notable feature is that bibliometric or review studies published in the same year focus on various elements of the subject and produce diverse results. In this regard, this chapter puts forth another bibliometric research, including the basic statistics, network relationships, and topic structures of the portfolio of articles in the relevant literature on digital twin technology enhanced with advanced visuals.

3 Methodology

Focusing on the concept and technology of the digital twin, the main objective of this research is to reveal the statistics and patterns regarding authors, co-authorship relationships, collaborations, journals, citations, keyword networks, and prominent topics and publication metrics in the relevant literature. Basic statistics, network relationships, and topic structures of the portfolio of articles are developed with advanced visuals. Thus, the research plan depends on these objectives and the related techniques of bibliometrics and scientometrics. The analyses were set to answer the following outcomes regarding the research on the concept of the digital twin:

- General distribution of the document types by years,
- Number of original articles by years,
- Impact of the articles in the related literature,
- Authors, countries, organizations and institutions, and collaborations among them,
- Journals and most cited articles,
- Thematic structures over author keywords.

In this context, related text and network analytics approaches are used along with bibliometrics and scientometrics methodologies. The study's data sources are the leading scientific databases Web of Science (WoS) and Scopus; the analyses focus on research articles published between 2010 and 2021 (June). We retrieved data based on the query "digital twin*" in a topic search.

3.1 Bibliometrics, Scientometrics, and Related Tools and Techniques

Activities to reveal the basic patterns of a particular subject in the literature, different topics and fields, connection points, and demographic elements are included in bibliometrics, scientometrics, informetrics, and webometrics as the techniques used within these methods. Although there are similarities in the focus, topics, and dimensions within the analysis, there are differences in the focus topics and dimensions within the analyses [8, 19, 28, 51]. Summary statistics on authors, keywords, and citations are provided in scientometric research. Furthermore, relationships such as co-authorship, co-citation, common keywords, and findings of advanced data analysis within the scope of time and clusters can be presented using network and density graphics in addition to summary statistics. Although the content and types of analyses are very similar in all similar methods, differences can be seen in the handling and details. For example, in the analyzes made within the scope of scientometrics, it is seen that the outputs are found in more dimensions [3]. In addition to descriptive statistics, network models and text analytics are employed in analyses [29]. Garfield [22] explained the historical development of scientometrics in detail in a chronological structure.

3.2 Preprocessing and Analysis

Different application environments such as Oracle database, WoS and Scopus analysis tools, Bibliometrix library in R [6], and spreadsheets were used for preprocessing, visualizations, and analysis. Several summary tables were organized to provide descriptive statistics for the selected dimensions. Also, appropriate software was utilized for further analyses, such as VOSviewer, i.e., the software package for analyzing and visualizing large bibliographic datasets. VOSviewer applies its modularity-based clustering similar to the multidimensional scaling based on the smart local moving algorithm [48, 49]. Within the scope of advanced data analysis, integrated network models with clustering analyzes have been developed to reveal the source perspectives of the research area, present the collaborations, thematic structure of keywords, and the journals in which the articles were published. These analyses first segment the raw data set, captured as plain text, using text analytics, create the network image over the metrics used in network analysis, and cluster it based on partnership levels and similarities. The findings were also discussed through the perspectives of fundamental laws of bibliometrics, i.e., Bradford's and Lotka's laws [13, 37].

4 Results and Findings

4.1 Overview of the Studies

The research on digital twin with Industry 4.0 was included in the analysis, as described in the methodology section. First and foremost, regardless of the category, the number of publications and summary visuals is displayed.

WoS databases comprise the following document types and frequencies (f); Articles (f:1,359), Proceedings Papers (f:921), Review Articles (f:123), Early Access (f:103), Editorial Materials (f:81), Book Chapters (f:26), Meeting Abstracts (f:7), News Items (f:5), Books (f:3), Corrections (f:2), Letters (f:2), Data Papers (f:1), respectively. In comparison to WoS, Scopus has a broader portfolio, i.e., Conference Paper (f:2266), Article (f:1757), Review (f:152), Conference Review (f:144), Book Chapter (f:141), Note (f:24), Editorial (f:21), Short Survey (f:13), Book (f:6), Erratum (f:2), Letter (f:2), Business Article (f:1), Data Paper (f:1), respectively.

There has been an upward tendency in recent years when we evaluate the impact of this article portfolio in WoS as evidenced by citation-based metrics such as Citing Articles (5091), Citing Articles Without self-citations (4352), Times Cited (10,028), Times Cited Without Self-Citations (6363), Average Citation Per Item (*ACP*) (7.38), *H*-Index (43). When we evaluate the impact of this article portfolio in Scopus as evidenced by citation-based metrics such as Times Cited (16,763), *ACP* (9.54), and *H*-Index (58), at this stage, we can speak of a significant effect in a relatively short timeframe, such as 2010–2021. This condition can be explained by exemplary studies

Table 1 Article counts by years

Years	Scopus		Web of Science	
	N	% in 1757 articles	*N*	% in 1359 articles
2021	762	43.36	537	39.51
2020	622	35.40	526	38.70
2019	256	14.57	206	15.15
2018	69	3.92	62	4.56
2017	41	2.33	24	1.76
2016	3	0.17	1	0.07
2015	2	0.11	2	0.14
2014	1	0.05	1	0.07
2013	0	0	0	0
2012	0	0	0	0
2011	1	0.05	0	0
2010	0	0	0	0

conducted by key industry sectors, research and development institutions, and, of course, academicians.

Further analyses are presented to see the field's detailed research patterns, focusing on the research articles created within the context of this topic after giving a broad overview of the number of publications (Table 1).

In keeping with the general profile, annual changes in the number of research articles within the selected period demonstrate an increasing trend, as seen in Table 1. As a result of this pattern, approximately, 79% of the chosen portfolio dates from the last two years. With new research in the coming months, this rate is expected to reach at least 80% by the end of the year. Preliminary studies on innovations and current issues in the scientific field are usually presented and discussed as proceedings or conference papers in symposiums, conferences, and similar scientific meetings. As a result, the number of articles published in proceeding books can also provide antecedent clues about the level of interest in a given subject and field. The statistics show a similar trend in the digital twin, reflected in conference papers in the same direction. From this vantage point, it is reasonable to expect this trend to continue to rise in the following years with positive momentum.

Another intriguing conclusion is that before 2017, just a few studies were included in the chosen portfolio. Although the literature review claims that the concept of a digital twin has been introduced and discussed since the early 2000s and that the idea of a digital twin has gained even more importance and interest since the announcement of the fourth industrial revolution in 2010, the dissemination of relevant research has accelerated when the required technology has become available.

4.2 Authors

The top 25 authors in both WoS and Scopus are given in Table 2 regarding the number of articles published (*N*) along with the total number of citations (*C*), *ACP*, and the percentage of the article count in the selected portfolio.

Generally, 4644 authors picked from WoS databases produced 1359 publications in the publication portfolio. While there are scholars dedicated to this topic, there are also those who have recently developed an interest in it or have published only a few papers on it as part of broader studies. The number of authors who publish ten or more publications within the context of the digital twin concept, for example, is ten. These leading authors, regarding the number of articles published, can be listed as Liu Q. (*f*:14; *C*:526; *ACP*:37.57); Soderberg R. (*f*:14; *C*:243; *ACP*:17.36), Tao F. (*f*:14; *C*:1,695; *ACP*:121.07), Leng J.W. (*f*:12; *C*:514; *ACP*:42.83), Warmefjord K. (*f*:12; *C*:190; *ACP* 15.83), Zhang H. (*f*:12; *C*:913; *ACP*:76.08), Zhang Y. (*f*:12; *C*:30; *ACP*:2.50), Chen X. (*f*:11; *C*:448; *ACP*:40.73), Li J. (*f*:10; *C*:86; *ACP*:8.60), Park K.T. (*f*:10; *C*:94; *ACP*:9.40), respectively. 59 researchers are observed in the list when the threshold is lowered to five.

1757 articles from the Scopus database yielded a total of 5727 authors. The number of writers with five or more publications is 154, which appears to be greater than WoS when adjusted by article count. In parallel with WoS, ten authors create ten or more articles. The WoS database has a higher proportion of authorial records than the other one on this level. Top ten authors regarding article counts are Tao, F. (*f*:31; *C*:3092; *ACP*:99.74), Qi, Q. (*f*:16; *C*:2128; *ACP*:133.00), Liu, J. (*f*:14; *C*:519; *ACP*:37.07), Liu, X. (*f*:13; *C*:264; *ACP*:20.30), Cheng, J. (*f*:11; *C*:1334; *ACP*:121.27), Leng, J. (*f*:11; *C*:629; *ACP*:57.18), Liu, Q. (*f*:11; *C*:768; *ACP*:69.81), Zhang, M. (*f*:11; *C*:2002; *ACP*:182.0), Zhuang, C. (*f*:11; *C*:358; *ACP*:32.54), Qu, T. (*f*:10; *C*:168; *ACP*:16.80), respectively.

It is also striking that the WoS and Scopus databases contain a significant difference between the top ten author lists, which have the intersection set in terms of the journals they host.

Lotka's law is one of the laws proposed in bibliometrics. It refers to the frequency with which authors in a given field publish. It shows that "*y* authors contributing *x* articles in a given period is a fraction of the number contributing a single article, based on the formula $x^n y$, where *n* nearly always equals two, i.e., an approximate inverse-square law, where the number of authors publishing a certain number of articles is a fixed ratio to the number of authors publishing a single article" [37: 323].

Lotka's law attempted to forecast the scientific productivity process to determine what contributions authors who wrote in a particular subject made to the literature and how their articles were quantitatively distributed in that field's literature [52: 62]. A Pareto-like distribution emerges when the number of contributions is plotted according to the number of authors [9: 23]. It is possible to assess the author's productivity status in the specified portfolio using the Bibliometrix library, available in the R coding environment. The findings of the analyses performed in this context are shown in Table 3.

Table 2 Top 25 authors according to the number of publications

Rank	Scopus					Web of Science				
	Authors	*N*	*C*	*ACP*	% in 1757 articles	Authors	*N*	*C*	*ACP*	% in 1359 articles
1	Tao, F.	31	3092	99.74	1.76	Liu, Q.	14	526	37.57	1.03
2	Qi, Q.	16	2128	133.00	0.91	Soderberg, R.	14	243	17.36	1.03
3	Liu, J.	14	519	37.07	0.79	Tao, F.	14	1695	121.07	1.03
4	Liu, X.	13	264	20.30	0.73	Leng, J. W.	12	514	42.83	0.88
5	Cheng, J.	11	1334	121.27	0.62	Warmefjord, K.	12	190	15.83	0.88
6	Leng, J.	11	629	57.18	0.62	Zhang, H.	12	913	76.08	0.88
7	Liu, Q.	11	768	69.81	0.62	Zhang, Y.	12	30	2.50	0.88
8	Zhang, M.	11	2002	182.00	0.62	Chen, X.	11	448	40.73	0.80
9	Zhuang, C.	11	358	32.54	0.62	Li, J.	10	86	8.60	0.73
10	Qu, T.	10	168	16.80	0.56	Park, K. T.	10	94	9.40	0.73
11	Hu, T.	9	473	52.55	0.51	Noh, S. D.	9	69	7.67	0.66
12	Liu, Z.	9	196	21.77	0.51	Zhang, M.	9	1004	111.56	0.66
13	Lu, Y.	9	422	46.88	0.51	Lu, Y. Q.	8	183	22.88	0.58
14	Park, K. T.	9	274	30.44	0.51	Rosen, R.	8	3	0.38	0.58
15	Söderberg, R.	9	285	31.66	0.51	Xu, X.	8	281	35.13	0.58
16	Wärmefjord, K.	9	285	31.66	0.51	Zhang, D.	8	321	40.13	0.58
17	Zhang, D.	9	444	49.33	0.51	Zhang, K.	8	23	2.88	0.58
18	Zhang, Y.	9	19	2.11	0.51	Chen, C. H.	7	163	23.29	0.51
19	Chen, X.	8	576	72.00	0.45	Lindkvist, L.	7	175	25.00	0.51
20	Noh, S. D.	8	105	13.12	0.45	Strube, J.	7	17	2.43	0.51

(continued)

Table 2 (continued)

Rank	Scopus					Web of Science				
	Authors	*N*	*C*	*ACP*	% in 1757 articles	Authors	*N*	*C*	*ACP*	% in 1359 articles
21	Stark, R.	8	109	13.62	0.45	Tan J. R.	7	25	3.57	0.51
22	Strube, J.	8	20	2.50	0.45	Zhang, C.	7	82	11.71	0.51
23	Xu, X.	8	382	47.75	0.45	Zheng, P.	7	175	25.00	0.51
24	Zhang, H.	8	1317	164.62	0.45	Huang, G. Q.	7	26	3.71	0.51
25	Bao, J.	7	101	14.42	0.39	Qu, T.	7	15	2.14	0.51

Table 3 Author productivity through Lotka's law

No. of articles	Scopus		Web of Science	
	No. of authors	Proportion of authors	No. of authors	Proportion of authors
1	3972	0.855	4358	0.832
2	439	0.095	506	0.097
3	123	0.026	141	0.027
4	50	0.011	79	0.015
5	22	0.005	43	0.008
6	12	0.003	21	0.004
7	9	0.002	25	0.005
8	5	0.001	16	0.003
9	2	0.000	8	0.002
10	2	0.000	5	0.001
11	1	0.000	5	0.001
12	4	0.001	1	0.000
13	0	0.000	6	0.001
14	3	0.001	3	0.001
15	0	0.000	4	0.001
16	0	0.000	1	0.000
17	0	0.000	4	0.001
18	0	0.000	2	0.000
19	0	0.000	2	0.000
20	0	0.000	1	0.000

When the WoS and Scopus data in Table 3 are evaluated, the number of researchers writing an article in the field is between 80 and 85% of the total researchers, while the number of researchers producing two documents in the area is between 9.5 and 9.7% and the number of researchers producing three articles is between 2.6 and 2.7%. When these results are evaluated together with the increasing trend in publications and citations, the digital twin is a current and open subject that has attracted significant attention from many authors in various fields.

A co-authorship network was developed to reveal the collaborations at the author level, as depicted in Fig. 1. The related clustering analysis was conducted in VOSviewer with the help of its original algorithm. The primary use parameter for co-authorship networks is the minimum number of documents as a threshold to appear on the network; therefore, two articles for WoS and four articles in Scopus were used by considering the total number of articles in each portfolio. In Fig. 1, the most productive authors in terms of the number of articles published seem to be the centroids of the corresponding clusters; moreover, the author groups in high collaboration are indicated in different colors.

Fig. 1 Co-authorships analysis by authors-based Web of Science and Scopus data countries

The article portfolio from WoS and Scopus databases has 72 different countries at its address. Although there are slight differences in the rankings, the top five countries are China, Germany, the USA, the UK, and Italy in both databases. These five countries remain dominant in half of the portfolio (Table 4). Countries in the top ten by the number of publications in Scopus are China (f:2,040), Germany (f:845), USA (f:628), UK (f:422), Italy (f:327), Spain (f:241), South Korea (f:239), France (f:189), Australia (f:112), Sweden (f:109), whereas in WoS, China (f:674), Germany (f:372), USA (f:363), UK (f:223), Italy (f:151), South Korea (f:120), France (f:109), Russia (f:109), Spain (f:102), Sweden (f:82), respectively. China is the leading country having 25% of the portfolio. Table 4 exhibits more countries in the top list to emphasize the other leading countries and the position of Turkey in this portfolio.

Table 4 Distribution of article counts by countries

Rank	Scopus				Web of Science			
	Countries/regions	*N*	*C*	% in 1757 articles	Countries/regions	*N*	*C*	% in 1359 articles
1	China	441	1982	25.09	China	290	3579	21.33
2	Germany	255	352	14.51	USA	204	1123	15.01
3	USA	210	265	11.95	Germany	192	1083	14.12
4	UK	144	439	8.19	UK	116	491	8.53
5	Italy	100	394	5.69	Italy	88	448	6.47
6	Russia	96	154	5.46	France	65	122	4.78
7	South Korea	68	145	3.87	South Korea	64	221	4.70
8	Spain	68	108	3.87	Spain	63	193	4.63
9	France	66	57	3.75	Sweden	50	294	3.67
10	Sweden	42	185	2.39	Russia	49	27	3.60
11	Hong Kong	40	34	2.27	Australia	37	242	2.72
12	Australia	39	143	2.21	India	36	86	2.64
13	India	35	53	1.99	Switzerland	35	47	2.57
14	Switzerland	35	53	1.99	Singapore	33	274	2.42
15	Norway	34	121	1.93	Netherlands	32	125	2.35
16	Singapore	32	94	1.82	Norway	32	123	2.35
17	Canada	31	13	1.76	Denmark	29	137	2.13
18	Denmark	28	62	1.59	Finland	28	112	2.06
19	Finland	28	24	1.59	Canada	27	222	1.98
20	Netherlands	28	42	1.59	Austria	22	48	1.61
21	Austria	26	66	1.47	Belgium	22	33	1.61
22	Belgium	22	9	1.25	Brazil	22	76	1.61
23	Greece	21	56	1.19	Greece	21	94	1.54
24	Poland	21	26	1.19	Poland	18	52	1.32
25	Japan	18	30	1.02	New Zealand	17	174	1.25
41	Turkey	6	5	0.34	Serbia	6	1	0.44
42					Turkey	6	6	0.44

Since more than one author mainly produces the articles, cross-country collaborations are worth examining within the scope of international partnerships. The country-based collaboration map and network in Fig. 2 were created due to the analyses carried out with the help of the Bibliometrix library in R. Figure 2 is consistent with Table 4 regarding the leading countries such that those countries constitute the cores of the clusters in the network. They also have most of the incoming flows in the collaboration map (Scopus). This map was developed using only the bibliometric data Scopus provided since the visualizations in WoS and Scopus are too close to each other. Presenting both of them might result in redundant figures in the text.

China, Hungary, Norway, Australia, Singapore, Canada, New Zealand, and Saudi Arabia are the highly collaborating countries in the red cluster around China. In the blue cluster, the UK and the USA are in the center of the clusters. Still, the USA has a more significant portfolio in the field where Korea, Sweden, Italy, Finland, Spain, Denmark, Belgium, Luxemburg, Thailand, Ireland, Estonia, United Arab Emirates, India, Cyprus, Greece, Switzerland, South Africa, and Pakistan are placed around these countries. The last and green cluster hosts Portugal, Czech Republic, Slovakia, Brazil, France, Austria, Romania, Germany, Netherlands, and Japan location Germany in the center. The numerous interactions of cluster centers should not be overlooked and considered when evaluating collaboration between more than two countries in detail.

Incorporating organizations and countries into the purview of bibliometric analysis yield valuable sub-dimension data. As a result, institutions to whom academics

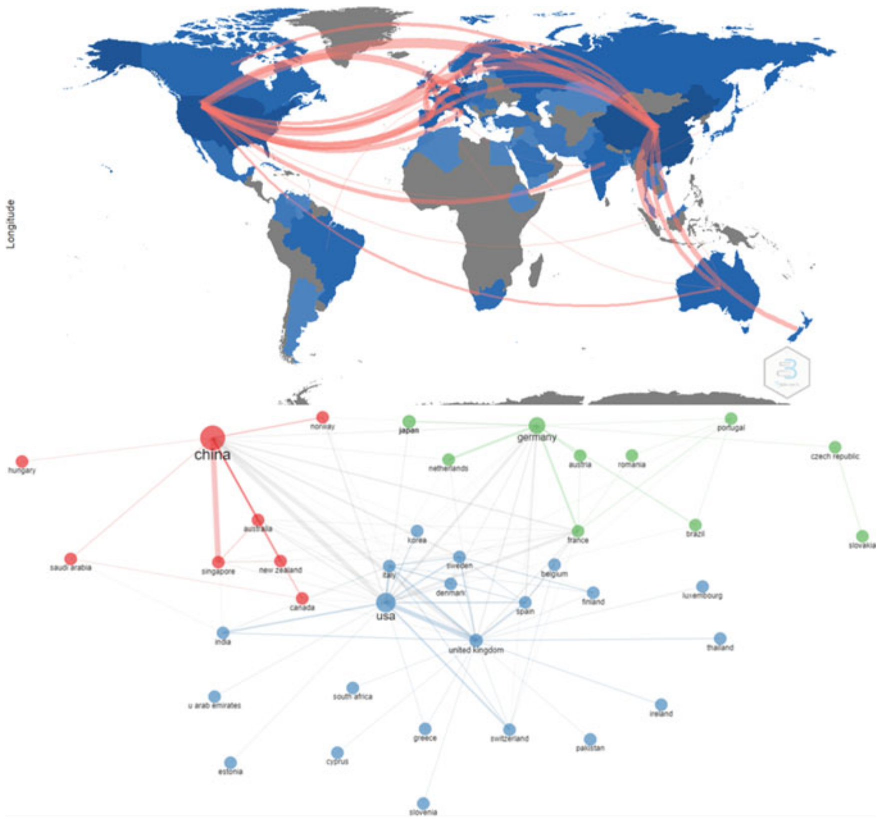

Fig. 2 Country-based collaboration map (minimum four edges) and collaboration network institutions and organizations

who desire to advance in this discipline can turn or examine collaboration options are offered. In this regard, gathering the information for institutions and organizations in WoS and Scopus regarding the digital twin concept, it is clear that German institutions stand out among those that provide a research environment for producing articles in both databases (Table 5 and Fig. 3). Rheinisch-Westfälische Technische Hochschule Aachen, Siemens AG, Universität Stuttgart, Technical University of Munich, Technische Universität Darmstadt, Friedrich-Alexander-Universität Erlangen-Nuremberg are some of Germany's most prestigious institutions. Furthermore, as illustrated in Fig. 2, European institutions have begun to collaborate more globally.

The other confronting institutions listed in Table 5 are China (Beihang University, Shanghai University, Shanghai Key Laboratory of Intelligent Manufacturing and Robotics), the UK (University of Cambridge, Cranfield University, The University of Sheffield), Russia (Peter the Great St. Petersburg Polytechnic University Russia, Saint Petersburg National Research University of Information Technologies, Mechanics and Optics University), in Italy (Politecnico di Milano, Politecnico di Torino), Norway (Norwegian University of Science Technology, DNV GL—Det Norske Veritas and Germanischer Lloyd—AS). It also stands out in digital twin scientific production with Finland, France, Hong Kong, Singapore, Greece, Sweden, Hungary, and New Zealand institutions.

Another notable discovery in Fig. 3 is that, while institution-level collaborations in Europe emerged as small clusters of two or three, more substantial and multiple links have been developed in clusters in the Far East, with locations like Hong Kong and China at the center.

4.3 Sources and Top Articles

The journals that distinguish out in bibliometrics research, as well as the articles published in these journals, are crucial in the analysis dimensions. Bradford's law is one of the first things that comes to mind at this point. Bradford's law defines how publications on a given topic are distributed. It is concerned with the submission of works to journals. Separation can be realized in core and other journals if scientific publications are managed according to this Law [13, 14]. According to Bradford, most publications on a given subject are published in a few journals devoted particularly to that topic or the main topic of which it is a part, and these journals constitute the field's core journals [13]. Doan (2019) emphasized this fact, stating that when a bibliography on a specific subject is sought, a small core set of journals will always contain a significant share (1/3) of the papers published in that subject or discipline. Therefore, sources can be categorized concerning Bradford's law, resulting in distinct zones. This law can also be adopted for managing and budgeting library resources, managing publications in order of priority and resource allocation, and deciding which journal databases to join on a field basis.

The statistics gathered at this level of the investigation are presented in three tables. Table 6 lists the journals that have published the most articles on digital twin,

Table 5 Distribution of article counts by institutions and organizations

Rank	Scopus				Web of Science			
	Institutions and organizations	Country	*N*	% in 1757 articles	Institutions and organizations	Country	*N*	% in 1359 articles
1	Rheinisch-Westfälische Technische Hochschule Aachen	Germany	50	2.84	Beihang University	China	29	2.13
2	Siemens AG	Germany	43	2.44	Centre National De La Recherche Scientifique	France	27	1.98
3	Peter the Great St. Petersburg Polytechnic University	Russia	40	2.27	University of Cambridge	UK	22	1.61
4	South Ural State University	Russia	31	1.76	Polytechnic University of Milan	Italy	20	1.47
5	Universität Stuttgart	Germany	30	1.70	Siemens AG	Germany	19	1.39
6	Technical University of Munich	Germany	27	1.53	Chalmers University of Technology	Sweden	18	1.32
7	Technische Universität Darmstadt	Germany	22	1.25	Helmholtz Association	Germany	18	1.32
8	The Saint Petersburg National Research University of Information Technologies, Mechanics and Optics University	Russia	20	1.13	Norwegian University of Science Technology	Norway	18	1.32
9	Chalmers University of Technology	Sweden	18	1.02	University of Hong Kong	Hong Kong	18	1.32
10	Norwegian University of Science Technology	Norway	18	1.02	National University of Singapore	Singapur	16	1.17
11	Politecnico di Milano	Italy	18	1.02	Siemens Germany	Germany	16	1.17

(continued)

Table 5 (continued)

Rank	Scopus				Web of Science			
	Institutions and organizations	Country	*N*	% in 1757 articles	Institutions and organizations	Country	*N*	% in 1359 articles
12	Budapest University of Technology and Economics	Hungary	17	0.96	University of Michigan	USA	16	1.17
13	Friedrich-Alexander-Universität Erlangen-Nürnberg	Germany	16	0.91	University of Michigan System	USA	16	1.17
14	University of Cambridge	UK	16	0.91	Guangdong University of Technology	China	15	1.10
15	Beihang University	China	15	0.85	US Department of Energy Doe	USA	15	1.10
16	Panepistimion Patron	Greece	15	0.85	University of Auckland	New Zealand	15	1.10
17	Aalto University	Finland	15	0.85	Beijing Institute of Technology	China	14	1.03
18	Cranfield University	UK	14	0.79	Northwestern Polytechnical University	China	14	1.03
19	Centre National de la Recherche Scientifique	France	13	0.73	Russian Academy of Sciences	Russia	14	1.03
20	Politecnico di Torino	Italy	13	0.73	Rwth Aachen University	Germany	14	1.03
21	Shanghai University	China	13	0.73	Sungkyunkwan University	South Korea	14	1.03

(continued)

Table 5 (continued)

Rank	Scopus				Web of Science			
	Institutions and organizations	Country	*N*	% in 1757 articles	Institutions and organizations	Country	*N*	% in 1359 articles
22	DNV GL (Det Norske Veritas and Germanischer Lloyd) AS	Norway	13	0.73	Cranfield University	UK	13	0.95
23	Shanghai Key Laboratory of Intelligent Manufacturing and Robotics	China	13	0.73	Fraunhofer Gesellschaft	Germany	13	0.95
24	The University of Sheffield	UK	12	0.68	Hong Kong Polytechnic University	Hong Kong	13	0.95
25	The University of Auckland	New Zealand	12	0.68	Jinan University	China	13	0.95

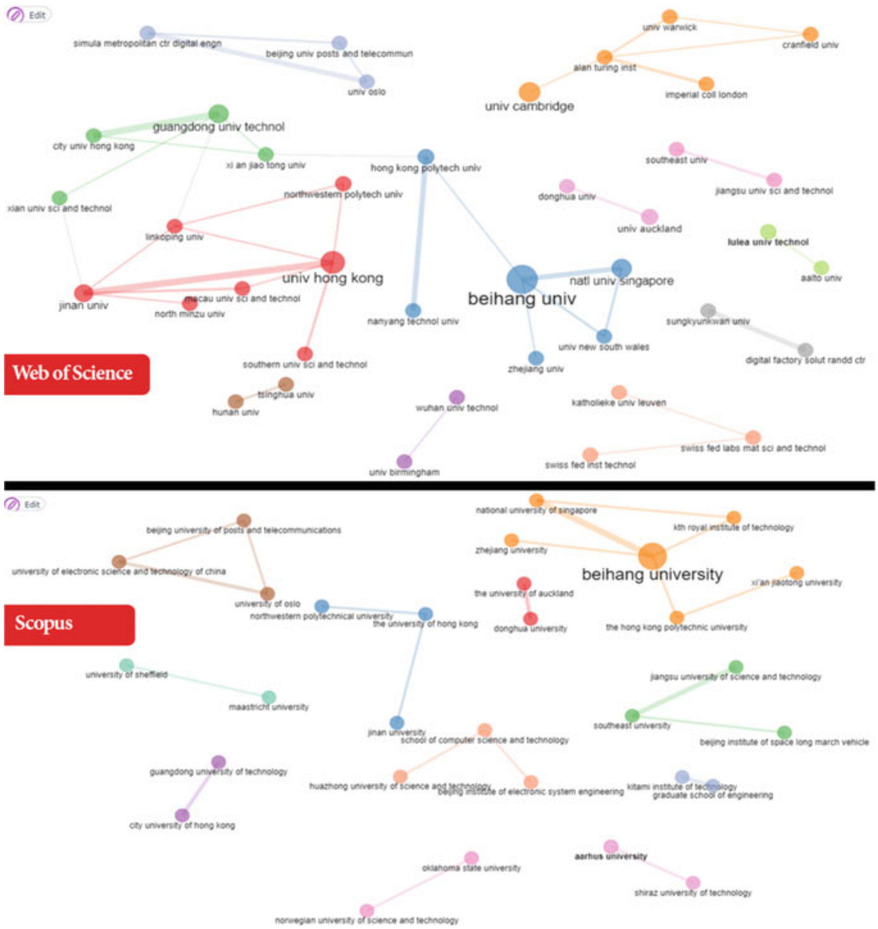

Fig. 3 Institutions and organizations-based collaboration networks

while Tables 7 and 8 list the top articles published in these journals as well as the most cited, or in other words, the top publications with the most significant influence in this subject. The journals were classified into different zones as a consequence of additional analyses of journal data within the scope of Bradford's law. It was observed that the portfolio of articles was published in 539 different journals in WoS and 691 in Scopus.

According to Bradford's law, 457 articles in Zone 1, home to 14 journals, account for 26% of the portfolio. WoS indexed journals in Zone 1 are IEEE Access (*f*:65), Applied Sciences-Basel (*f*:60), Journal of Manufacturing Systems (*f*:45), International Journal of Advanced Manufacturing Technology (*f*:40), Sensors (*f*:39), Sustainability (*f*:32), International Journal of Computer Integrated Manufacturing

Table 6 Top 25 journals in Scopus and WoS

Rank	Scopus			Web of Science		
	Publication titles	*N*	% in 1757 articles	Publication titles	*N*	% in 1359 articles
1	Jisuanji Jicheng Zhizao Xitong Computer Integrated Manufacturing Systems	74	4.21	IEEE Access	65	4.78
2	Applied Sciences Switzerland	64	3.64	Applied Sciences Basel	60	4.41
3	IEEE Access	57	3.24	Journal of Manufacturing Systems	45	3.31
4	Journal of Manufacturing Systems	54	3.07	International Journal of Advanced Manufacturing Technology	39	2.87
5	ZWF Zeitschrift Fuer Wirtschaftlichen Fabrikbetrieb	38	2.16	Sensors	39	2.87
6	International Journal of Advanced Manufacturing Technology	35	1.99	Sustainability	32	2.35
7	Sustainability Switzerland	30	1.70	International Journal of Computer Integrated Manufacturing	26	1.91
8	International Journal of Computer Integrated Manufacturing	28	1.59	International Journal of Production Research	26	1.91
9	Sensors Switzerland	27	1.53	Robotics And Computer Integrated Manufacturing	23	1.69
10	IEEE Transactions on Industrial Informatics	23	1.30	CIRP Annals Manufacturing Technology	22	1.61
11	Robotics And Computer Integrated Manufacturing	23	1.30	Ercim News	21	1.54
12	Energies	20	1.13	Energies	20	1.47

(continued)

Table 6 (continued)

Rank	Scopus			Web of Science		
	Publication titles	*N*	% in 1757 articles	Publication titles	*N*	% in 1359 articles
13	International Journal of Production Research	20	1.13	Processes	20	1.47
14	Processes	18	1.02	Journal of Cleaner Production	17	1.25
15	CIRP Annals	17	0.96	ATP Magazine	16	1.17
16	Journal of Computing and Information Science In Engineering	16	0.91	Journal of Computing And Information Science in Engineering	15	1.10
17	Sensors	14	0.79	IEEE Transactions on Industrial Informatics	14	1.03
18	Advances In Biochemical Engineering Biotechnology	13	0.73	Journal of Intelligent Manufacturing	14	1.03
19	IEEE Internet Computing	13	0.73	Automation in Construction	12	0.88
20	Journal of Cleaner Production	13	0.73	Advances in Computers	10	0.73
21	Automation In Construction	12	0.68	Digital Twin Paradigm for Smarter Systems and Environments The Industry Use Cases	10	0.73
22	IEEE Internet of Things Journal	12	0.68	Journal of Management in Engineering	10	0.73
23	Journal of Intelligent Manufacturing	11	0.62	Engineering Fracture Mechanics	9	0.66
24	Russian Engineering Research	11	0.62	Journal of Ambient Intelligence and Humanized Computing	9	0.66
25	Journal of Management in Engineering	10	0.56	Advances in Civil Engineering	8	0.58

Table 7 Most cited articles in Scopus

Rank	Title	Journal	Authors	Year	*C*
1	Digital twin-driven product design, manufacturing, and service with big data	International Journal of Advanced Manufacturing Technology	Tao, F., Cheng, J., Qi, Q., Zhang, M., Zhang, H., Sui, F.	2018	746
2	Shaping the digital twin for design and production engineering	CIRP Annals—Manufacturing Technology	Schleich, B., Anwer, N., Mathieu, L., Wartzack, S.	2017	406
3	Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison	IEEE Access	Qi, Q., Tao, F.	2018	377
4	A Review of the Roles of Digital Twin in CPS-based Production Systems	Procedia Manufacturing	Negri, E., Fumagalli, L., Macchi, M.	2017	372
5	Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing	IEEE Access	Tao, F., Zhang, M.	2017	351
6	Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case	Transportation Research Part E: Logistics and Transportation Review	Ivanov, D.	2020	348
7	Reengineering aircraft structural life prediction using a digital twin	International Journal of Aerospace Engineering	Tuegel, E. J., Ingraffea, A. R., Eason, T. G., Spottswood, S. M.	2011	338
8	Digital Twin in Industry: State-of-the-Art	IEEE Transactions on Industrial Informatics	Tao, F., Zhang, H., Liu, A., Nee, A. Y. C.	2019	281
9	C2PS: A digital twin architecture reference model for the cloud-based cyber-physical systems	IEEE Access	Alam, K. M., El Saddik, A.	2017	261
10	Toward a Digital Twin for real-time geometry assurance in individualized production	CIRP Annals—Manufacturing Technology	Soderberg, R., Warmefjord, K., Carlson, J. S., Lindkvist, L.	2017	214

(continued)

Table 7 (continued)

Rank	Title	Journal	Authors	Year	*C*
11	Digital twin-driven product design framework	International Journal of Production Research	Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., Guo, Z., Lu, S. C. -Y., Nee, A. Y. C.	2019	182
12	Digital twin-based smart production management and control framework for the complex product assembly shop-floor	International Journal of Advanced Manufacturing Technology	Zhuang, C., Liu, J., Xiong, H.	2018	182
13	Digital twin workshop: a new paradigm for future workshop	Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems, CIMS	Tao, F., Zhang, M., Cheng, J., Qi, Q.	2017	173
14	Digital Twins: The Convergence of Multimedia Technologies	IEEE Multimedia	El Saddik, A.	2018	172
15	Digital twin-driven prognostics and health management for complex equipment	CIRP Annals	Tao, F., Zhang, M., Liu, Y., Nee, A. Y. C.	2018	166
16	The Digital Twin: Demonstrating the Potential of Real Time Data Acquisition in Production Systems	Procedia Manufacturing	Uhlemann, T. H. -J., Schock, C., Lehmann, C., Freiberger, S., Steinhilper, R.	2017	166
17	Customer experience challenges: bringing together digital, physical and social realms	Journal of Service Management	Bolton, R. N., McColl-Kennedy, J. R., Cheung, L., Gallan, A., Orsingher, C., Witell, L.,Zaki, M.	2018	154
18	A Digital Twin-Based Approach for Designing and Multi-Objective Optimization of Hollow Glass Production Line	IEEE Access	Zhang, H., Liu, Q., Chen, X., Zhang, D., Leng, J.	2017	152
19	Digital Twins and Cyber-Physical Systems toward Smart Manufacturing and Industry 4.0: Correlation and Comparison	Engineering	Tao, F., Qi, Q., Wang, L., Nee, A. Y. C.	2019	141

(continued)

Table 7 (continued)

Rank	Title	Journal	Authors	Year	*C*
20	A systematic design approach for service innovation of smart product-service systems	Journal of Cleaner Production	Zheng, P., Lin, T. -J., Chen, C. -H., Xu, X.	2018	141

Table 8 Most cited articles in WoS

Rank	Title	Journal	Authors	Year	C
1	Digital twin-driven product design, manufacturing and service with big data	International Journal of Advanced Manufacturing Technology	Fei, T., Jiangfeng, C., Qinglin, Q., Zhang, M., Zhang, H., Fangyuan, S.	2018	505
2	Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case	Transportation Research Part E-Logistics and Transportation Review	Ivanov, D.	2020	288
3	Digital Twin and Big Data Towards Smart Manufacturing and Industry 4.0: 360 Degree Comparison	IEEE Access	Qi, Q. L.; Tao, F.	2018	260
4	Shaping the digital twin for design and production engineering	CIRP Annals-Manufacturing Technology	Schleich, B., Anwer, N., Mathieu, L., Wartzack, S	2017	257
5	Digital Twin Shop-Floor: A New Shop-Floor Paradigm Towards Smart Manufacturing	IEEE Access	Tao, F., Zhang, H.	2017	223
6	The future of manufacturing industry: a strategic roadmap toward Industry 4.0	Journal of Manufacturing Technology Management	Ghobakhloo, M.	2018	222
7	Digital Twin in Industry: State-of-the-Art	IEEE Transactions on Industrial Informatics	Tao, F., Zhang, H., Liu, A., & Nee, A. Y	2019	198
8	C2PS: A Digital Twin Architecture Reference Model for the Cloud-Based Cyber-Physical Systems	IEEE Access	Alam, K. M.; El Saddik, A.	2017	186

(continued)

Table 8 (continued)

Rank	Title	Journal	Authors	Year	C
9	Toward a Digital Twin for real-time geometry assurance in individualized production	CIRP Annals-Manufacturing Technology	Söderberg, R., Wärmefjord, K., Carlson, J. S., Lindkvist, L.	2017	143
10	Digital twin-driven product design framework	International Journal of Production Research	Tao, F., Sui, F., Liu, A., Qi, Q., Zhang, M., Song, B., …, Nee, A. Y.	2019	131
11	Digital twin-driven prognostics and health management for complex equipment	CIRP Annals-Manufacturing Technology	Tao, F., Zhang, M., Liu, Y., & Nee, A. Y.	2018	123
12	Digital twin-based smart production management and control framework for the complex product assembly shop-floor	International Journal of Advanced Manufacturing Technology	Zhuang, C. B., Liu, J. H., Xiong, H.	2018	116
13	Customer experience challenges: bringing together digital, physical and social realms	Journal of Service Management	Bolton, R. N., McColl-Kennedy, J. R., Cheung, L., Gallan, A., Orsingher, C., Witell, L., Zaki, M.	2018	107
14	A systematic design approach for service innovation of smart product-service systems	Journal of Cleaner Production	Zheng, P., Lin, T. J., Chen, C. H., & Xu, X.	2018	106
15	Digital twin-driven rapid individualised designing of automated flow-shop manufacturing system	International Journal of Production Research	Liu, Q., Zhang, H., Leng, J., & Chen, X.	2019	102
16	A Digital Twin-Based Approach for Designing and Multi-Objective Optimization of Hollow Glass Production Line	IEEE Access	Zhang, H., Liu, Q., Chen, X., Zhang, D., & Leng, J.	2017	102
17	Building blocks for a digital twin of additive manufacturing	Acta Materialia	Knapp, G. L., Mukherjee, T., Zuback, J. S., Wei, H. L., Palmer, T. A., De, A., & DebRoy, T. J. A. M.	2017	99

(continued)

Table 8 (continued)

Rank	Title	Journal	Authors	Year	C
18	Digital twin-driven manufacturing cyber-physical system for parallel controlling of smart workshop	Journal of Ambient Intelligence and Humanized Computing	Leng, J., Zhang, H., Yan, D., Liu, Q., Chen, X., & Zhang, D.	2019	94
19	Defining a Digital Twin-based Cyber-Physical Production System for autonomous manufacturing in smart shop floors	International Journal of Production Research	Ding, K., Chan, F. T., Zhang, X., Zhou, G., Zhang, F.	2019	92
20	A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0	Production Planning & Control	Ivanov, D., Dolgui, A.	2021	91

(*f*:27), International Journal of Production Research (*f*:26), Robotics and Computer-Integrated Manufacturing (*f*:23), CIRP Annals-Manufacturing Technology (*f*:22), Ercim News (*f*:21), Energies (*f*:20), Processes (*f*:20), Journal of Cleaner Production (*f*:17), respectively. Zone 2 comprises 116 journals and 461 articles, whereas Zone 3 comprises 409 journals and 441 articles.

According to Scopus data, there are 19 journals in Zone 1, and 558 articles published in these journals, contributing to 31% of all articles. The number of journals in Zone 2 is 99, with 333 papers published, and the number of journals in Zone 3 is 573, with 866 articles. Journals in Zone 1 that are indexed in Scopus but not included in WoS databases are Jisuanji Jicheng Zhizao Xitong/Computer Integrated Manufacturing Systems (*f*:74), ZWF Zeitschrift Fuer Wirtschaftlichen Fabrikbetrieb (*f*:38), IEEE Transactions on Industrial Informatics (*f*:23), Journal of Computing and Information Science in Engineering (*f*:16), Advances in Biochemical Engineering/Biotechnology (*f*:13), IEEE Internet Computing (*f*:13), respectively.

Researchers may primarily monitor the field thanks to Bradford's law, publish their papers in relevant journals, receive more citations from related journals, and allow more researchers to review and evaluate their work. Of course, the journals in Zone 1 and the top 25 magazines with the highest number of articles, as determined by WoS and Scopus data in Table 6, can be described as the fields they will select as a source of publishing for both following and contributing to the area.

The citation information for the top 20 most cited works in the WoS and Scopus databases (Tables 7 and 8) is "Fei, T., Jiangfeng, C., Qinglin, Q., Zhang, M., Zhang, H., & Fangyuan, S. (2018). Digital twin-driven product design, manufacturing and service with big data. The International Journal of Advanced Manufacturing Technology, 94(9–12), 3563–3576." This article has been cited 505 times in WoS and 746 times in Scopus. The same work has varying citation numbers in two bibliometric databases since they can only manage the citations delivered to the relevant works through their source pool.

When Tables 2, 7, and 8 are combined, it is clear that Tao, F. has five papers in WoS and eight in Scopus in the list of the most cited papers. Another discovery is that Cheng, J. has collaborated widely and participated in collaborative and highly cited research with Leng, J., Liu, Q., and Zhang, M.

Furthermore, the presence of Chinese researchers among the most cited works implies that Chinese researchers have had a significant impact on the development of this research topic and have leading institutions in this field, as depicted in Fig. 3. It is recommended that researchers interested in researching this topic as doctoral or postdoctoral researchers should pay special attention to China and its institutions.

4.4 The Related Research Areas, Keywords, and Potential Topics

Park et al. [41:596] highlighted that the utilities of the industrial Internet of things, connected microsmart factories in factory-as-a-service systems are suboptimal in cost and throughput. A digital twin was created and deployed, employing a digital process model with the identical setup of manufacturing parts, synchronized information, and functional units. The digital twin notion is a phenomenon that can generate solutions in terms of sustainability, profitability, efficiency, and competitiveness for industries that can employ this technology and institutions and researchers who provide the advancement of digital twin technology. It has begun to take place in the focus of production enterprises in particular. When looking at the research topics in the literature, it is clear that they are likewise centered in this setting. When the research areas (e.g., Engineering, Computer Science, and Materials Science) centered on the research papers collected from the WoS and Scopus databases are assessed, this pattern may be seen more clearly in Table 9.

When the keywords were analyzed, it was discovered that there were 4425 researcher keywords used in 1359 papers in WoS, with 700 terms appearing twice or more, 143 words appearing five times or more, and 43 words appearing ten times or more. Meanwhile, in Scopus, 5266 keywords are utilized, with 814 repeating two or more times, 152 for five or more, and 52 for ten or more.

When the research articles obtained from both sources are evaluated by keyword and subject-specific, it is discovered that the most intensely discussed topics with the digital twin topic are Industry 4.0 [18], simulation, Internet of things, smart manufacturing, blockchain, ontology, big data, 3D printers, and 3D modeling, cyber-physical system, robotics, cloud computing, 5G mobile communication, digitalization, network architecture, and blockchain.

Figures 4 and 5 show the factorial analysis topic dendrogram results over WoS and Scopus data, demonstrating this condition. Actually, this circumstance indicates which technologies are involved in the change we are through and which technologies are being incorporated to help the digital twin issue go more smoothly. Cyber-physical systems and digital twins, for example, are piquing the interest of industry

Table 9 Research areas that the concept of digital twin are covered

Rank	Scopus			Web of Science		
	Research areas	*N*	% in 1757 articles	Research areas	*N*	% in 1359 articles
1	Engineering	1260	71.71	Engineering	840	61.81
2	Computer Science	798	45.41	Computer Science	340	25.01
3	Materials Science	263	14.96	Materials Science	134	9.86
4	Physics and Astronomy	201	11.43	Operations Research Management Science	123	9.05
5	Business, Management and Accounting	177	10.07	Chemistry	120	8.83
6	Energy	164	9.33	Telecommunications	108	7.94
7	Chemical Engineering	159	9.04	Science Technology Other Topics	104	7.65
8	Mathematics	159	9.04	Automation Control Systems	95	6.99
9	Environmental Science	126	7.17	Physics	87	6.40
10	Decision Sciences	111	6.31	Environmental Sciences Ecology	65	4.78
11	Social Sciences	110	6.26	Instruments Instrumentation	64	4.70
12	Biochemistry, Genetics and Molecular Biology	88	5.00	Energy Fuels	59	4.34
13	Chemistry	77	4.38	Mechanics	42	3.09
14	Earth and Planetary Sciences	74	4.21	Construction Building Technology	41	3.01
15	Medicine	30	1.70	Mathematics	32	2.35
16	Agricultural and Biological Sciences	18	1.02	Robotics	30	2.20
17	Economics, Econometrics and Finance	18	1.02	Business Economics	24	1.76
18	Immunology and Microbiology	18	1.02	Remote Sensing	23	1.69
19	Multidisciplinary	18	1.02	Metallurgy Metallurgical Engineering	20	1.47
20	Arts and Humanities	14	0.79	Thermodynamics	17	1.25

(continued)

Table 9 (continued)

Rank	Scopus			Web of Science		
	Research areas	*N*	% in 1757 articles	Research areas	*N*	% in 1359 articles
21	Pharmacology, Toxicology and Pharmaceutics	14	0.79	Geology	14	1.03
22	Health Professions	6	0.34	Oceanography	14	1.03
23	Neuroscience	3	0.17	Biotechnology Applied Microbiology	11	0.80
24	Psychology	3	0.17	Mining Mineral Processing	11	0.80
25	Nursing	1	0.05	Transportation	10	0.73

researchers and practitioners. Cyber-physical integration, which manufacturers are rapidly adopting, is a crucial prerequisite for smart production [47: 653]. Physical systems operate as sensors to collect real-world data and transfer it to processing modules, which then analyze and notify the findings to the associated physical systems through a feedback loop [4:2050].

Tao et al. [46:20418] stated that "a smart manufacturing era is coming" due to the advancements and applications of new information technologies such as cloud computing, the Internet of things, big data, and artificial intelligence. Dai [18:1]

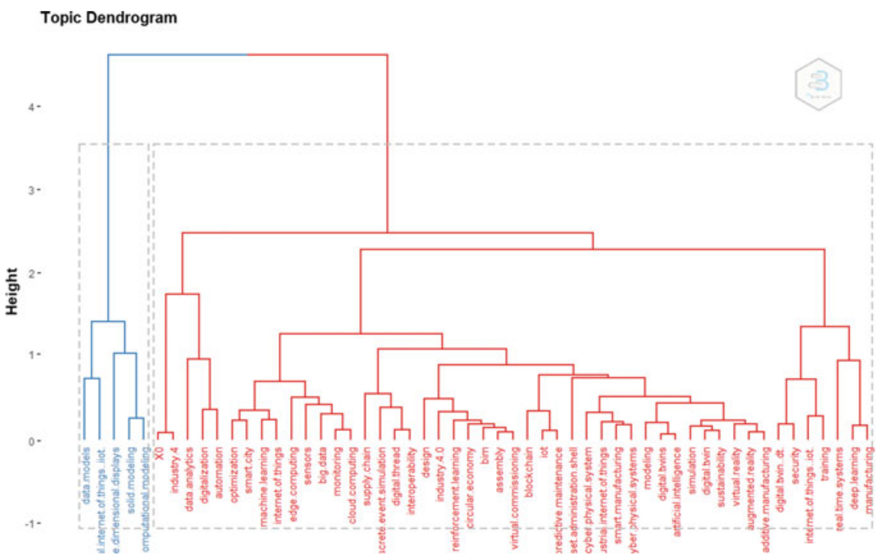

Fig. 4 Conceptual structure-factorial analysis topic dendrogram (WoS)

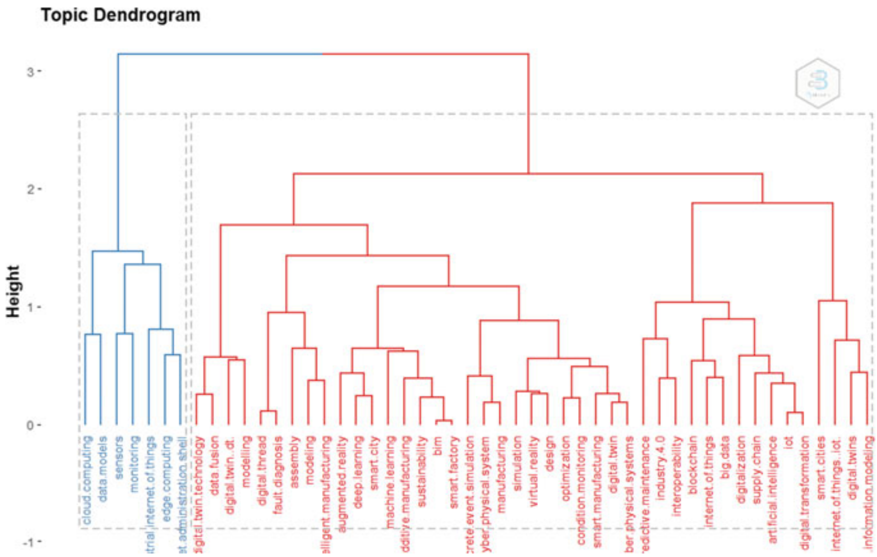

Fig. 5 Conceptual structure-factorial analysis topic dendrogram (Scopus)

emphasized the digital twin idea, as the leading edge of digital manufacturing solutions for modern industries, plays a vital role in the Industry 4.0 era. They described the main activities as follows:

- Accessing the sensor information from the production lines to the primary machines over the network.
- The data processed rapidly by machine learning or artificial intelligence determine the ideal production parameters with optimization for the way the robots work and monitoring and evaluation in real-time.
- Storing, keeping, analyzing, and improving logs, sensor data, outputs of processes, and many more with cloud computing technology; determining the optimum system parameters on the digital twin and transferring them to the physical system in real-time.
- Technological possibilities such as operating production schemes at different nodes on an encrypted blockchain indicate how smart manufacturing and smart factory.

The Internet of things provides vital links for communication between digital twins' components. The Internet of things allows an item to connect and interact with other devices using sensors, internet lines, and software. As a result, the physical thing in question can be remotely observed and controlled with the help of this technology which also allows for real-time updates to the digital models under investigation. As a result, it is not surprising that the digital twin issue is a common topic in many studies.

The use of information-based machine learning and deep learning systems, building ideal processes and supporting management decisions are the most critical areas in which studies are generally piled up and at the forefront of the research. Knowledge-based systems, along with machine learning, deep learning, and artificial intelligence technologies, are utilized to estimate the best feasible scenario. The related concepts in the portfolio of selected articles are revealed as knowledge-based systems, neural networks, data analytics, data acquisition, digital transformation, decision support systems, data visualization, data integration, data fusion, data mining, predictive maintenance, and data handling, along with abovementioned approaches.

The research on digital twins may also be observed in the improvement of production lines, quality control, control systems, risk assessment, process control, optimization, fault detection, and digital twin research is where digital twin can be used. Alam and El Saddik [4:2050] claimed that sensors and actuators have become more inexpensive and accessible. As a result, the digital twin technology of flexible sensors has progressed well. The data collected from sensors via computer networks are used to activate the physical system via computer systems.

Another concept in research published on a digital twin is smart connected products. A smart and connected product is the third wave of IT competition, transforming how value is produced by integrating IT into the physical good or any output [42]. The booming of information and communications technology development and implementation has triggered the flourish of a promising smart and connected product market and benefits manufacturing companies' servitization toward a smart product-service systems value proposition [53:666].

The hot topics that are used and focused on in related research in this direction are; smart, automation, quality control, manufacture, production control, uncertainty, and manufacturing analysis, risk assessment, supply chains, operation and maintenance, real-time monitoring, real-time systems, real-time simulation, product life cycle, control systems, fault detection, cyber-physical system, product design, machine tools, maintenance, production system, additive manufacturing, production, process control, computer-aided design, optimization. In new-generation intelligent manufacturing, also known as smart manufacturing, smart technologies such as the Internet of things, cloud computing, big data analytics, cyber-physical systems, and digital twins have been located in the center. It was also stated that smart manufacturing provides an organizational environment that meets the needs for socialization, personalization, servitization, intelligence, and greenization [36, 46:20418, 54, 55].

The smart city, building industry, energy, health, and aircraft sectors are among the topics that have been widely investigated and brought to the fore on the digital twin. Building information models and building information modeling are heavily researched, particularly in the construction industry [27, 40, 56]. The subject of structural health monitoring the healthcare [35, 38], in the energy industry, energy utilization, energy efficiency, and sustainability [11, 50] are the hot topics that are studied together with digital twin technology. Starting the research on related issues is helpful for academics interested in the digital twin and the construction or health sectors or who wish to specialize in this field. For example, in health care, [35:49088] emphasized that a simulation is an integral approach, especially for the developments in medical planning, resource allocation, and activity prediction. Combining digital twin with healthcare would result in a novel and effective method for delivering more precise and quick services for geriatric healthcare.

Naturally, the digital twin as a research topic has been handled along with software, hardware, and technology developments. This fact has also been demonstrated by the papers gathered from WoS and Scopus. One can find several use cases that have integrated digital twin, computer, sensor, and software technologies which allow the creation of diverse scenarios using models created on physical assets or the physical side of the twin, such as smart manufacturing lines, smart buildings, and equipment, which and then transfer to the digital world. By doing so, the relevant data on the state of physical assets is acquired using sensors, and the digital simulation is automatically updated using software [7, 20, 21, 43]. The most intensively investigated and discussed topics on computer and software technology along with digital twin are found to be embedded systems, computer simulation, Bayesian networks, Monte Carlo methods, computer software, algorithm, genetic algorithms, learning algorithms, semantics, cyber-physical system, computer control systems, decision making, intelligent manufacturing, digital representations, computer architecture, three-dimensional computer graphics, sensors, digitization, and systems engineering.

Another field where the digital twin is handled intensively is education. E-learning, learning management systems, engineering education, modeling, augmented reality, virtual reality, and human–robot collaboration are the hot topics that are intensively studied for more efficient progress of the related industry and the improvement of the quality of the workforce trained in the industry [10, 23, 26, 34].

Particularly in physics and astronomy (Table 9), the technologies that constitute the foundation of digital twin technology are being developed to satisfy the demands of space studies. Digital twin technology, which provides all possibilities for the training, testing, maintenance, management, and monitoring processes of space technologies and other related equipment designed for particular purposes, is increasingly being used in conjunction with other associated technologies such as augmented reality, virtual reality, and human–robot collaboration, and researchers in this field also pursue new research that will respond to these challenges.

5 Conclusion

Process simulation models with direct connections to flowing data through the related processes have been pushing applications of real-time methods with the introduction of Industry 4.0. This new situation allows for creating digital twin models, which provides a reliable analysis platform for visualizing and optimizing data in production environments designed with smart technologies.

While practices and research and development activities on the digital twin concept and related technologies continue to overgrow, scientific publications that explain these activities, share experiences, and make recommendations for future research can also be found in the literature. Studies evaluating and reviewing the trends followed by this rapidly expanding publishing portfolio, the topics it focuses on, the challenges it addresses, and the methodologies it employs are equally important in assessing the current situation and giving insight into future research. Section 2 provided several reviews, systematic reviews, and bibliometric studies on digital twins and associated application fields. Each of them holistically portrays the scenario in their period using variables established in the study design, such as author, journal, citation, and subject.

In addition to the review of past studies in this context, we conducted a new bibliometric study that focused on the general patterns of related research presented in a timeframe from 2010, the year when the concept of Industry 4.0 to the date of data collection (June 2021) over related bibliometric data (articles) of WoS and Scopus, as defined in our research plan. The analyses were conducted using more inferential and sophisticated statistics such as clustering, factor, and network analysis, as well as descriptive and basic statistics, which extract general frequency distributions in many dimensions and depict available patterns regarding authors, countries, institutions and organizations, journals, collaborations, topics, citations, and related metrics. The Bibliometrix library, which executes on the R platform, and the necessary interfaces were used to implement these analyses.

Compared to earlier systematic reviews and bibliometric studies, prominent researchers in the field of digital twin continue providing new research. Still, numerous researchers force the ranks regarding the number of publications and citations with their productivity. Although the most cited article has remained unchanged, it has been noted that the old rankings of the articles have been modified. Furthermore, this chapter also provided results in a broader sense by adding more dimensions, e.g., countries, institutions, journals, and collaborations over these dimensions.

During the selected timeframe, the related research has primarily focused on the creation of the essential technology components for the digital twin; the formation of digital twin supported models within the context of smart or digital manufacturing; building sophisticated data analysis and optimization models based on artificial intelligence and big data analytics; the use of digital twin models for assistance and training in a variety of disciplines, as well as their integration with various technologies. All the findings showed that the digital twin as a research topic is one of the most critical technologies for the industrial revolution. It integrates and systematically interacts with many technologies such as cloud computing, big data, computer-aided systems, sensors, deep learning, machine learning, cyber-physical systems, and blockchain.

The existence of concepts such as blockchain, supply chain, additive manufacturing, optimization, modeling, reinforcement learning, predictive maintenance, monitoring, augmented reality, and interoperability, which are not prominent in previous studies, but stand out in the thematic analyzes of this study, is the presence of many findings such that digital twin technologies and models have not stacked in the design or prototype stage; on the contrary, it is now at implementation and analysis stage. Our findings supported this idea with the revealed conceptual structure that articles on the digital twin concept also covered integrations with other technologies, production management, and planning approaches. These findings can also be considered an indicator of the application of advanced optimization and machine learning algorithms in monitoring and improving digital twin models.

On the other hand, the analysis of digital twin models and related organizational research has been relatively limited. Even though robots and robot software have displaced people from many routine and regular jobs, these systems and high-tech goods' design, administration, and operation will still require human labor due to rapid technological advancements. Researchers of organizational behavior and human resources, in particular, may research human positions, new job definitions, different competencies, authorities, and responsibilities for digital twin and related processes; therefore, they may complete the organizational aspect of these systems in addition to the economic and technological aspects.

As a result, with this study, we have presented the studies on digital twin technology and models, which have been carried out since the announcement of Industry 4.02, from a broad perspective with the bibliometric research method, and we have revealed the dynamics of this field holistically in a big picture frame. We present this section to the readers' attention hoping that the study's findings will guide researchers and practitioners to help them understand the current developments; observe the dynamics and demographics; make literature survey plans and support their topic selection.

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Towards Developing a Digital Twin for a Manufacturing Pilot Line: An Industrial Case Study

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1 Introduction

Increasing manufacturing customization, reducing the manufacturing cost and CO_2 emissions, faster system verification and validation are goals that have been sought in industry. Smart manufacturing and Industry 4.0, assisted by different technologies, are introduced to make these objectives possible. Digital twin (DT), the virtual counterpart of a physical entity, is one of the current concepts of Industry 4.0 that has gained attention both in industry and academia [1]. A DT can simultaneously represent, monitor, optimize, and control the physical replica [2].

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_2

1.1 Definitions of Digital Twins

Different academics and industrial practitioners have defined DTs over the past years, but most of these definitions touch upon the same concepts [3, 4]. One of the first definitions of the DT comes from NASA and the US Air Force Research Laboratory, which referred to DT as “an integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, and so forth, to mirror the life of its flying twin” [5]. However, nowadays, DT is defined by a broader definition as a virtual replica that continuously updates and represents products, assets, personnel, or processes and adapts synchronously to depict changes in geometric characteristics, resource states, or working conditions [6].

1.2 Elements

Different vital elements of DTs are referred to as dimensions, and according to the literature, DTs can include three or five dimensions [3]. The basic three-dimension model of DT points out the physical entity, virtual counterpart, and the connection as the main DT elements. Later, a five-dimensional definition of DT was proposed by Tao et al. [7], which introduced the services that DT provides, and the data transferred between two entities as vital elements of DT.

1.3 Enabling Technology

Five-dimension DT emphasizes the need for a high-fidelity model with a comprehensive perception of the environment. For this purpose, different sensing technologies are needed to make the virtual model aware of the physical entity status. Furthermore, different big data analytics methods are needed due to the large volume of data. Moreover, for transmitting data between the twins, different communication protocols are needed [8].

1.4 Case Study

This case study focuses on developing a DT for an industrial manufacturing prototype with multiple steps. The adjustments and assembly of several components and subassemblies are performed at speeds suitable for high-volume production. Therefore, the data collection is implemented with a mature method, and all equipment and process signals from various sensors are organized as a database. Furthermore, the details related to the assembly machine, the product, and the process of interest are explained in Sect. 3.

Standard programmable logic controller (PLC) data collection mechanisms are typically limited by a sampling rate that is considerably lower than the scan cycle at which the PLCs operate, e.g., 100 ms intervals versus 5 μs scan cycles. For the data collection to keep up with the scan cycle speed, we employ a Kafka-based ingestion solution where data are buffered and transmitted efficiently from the PLC to a Kafka broker running on standard PC hardware [9]. Using Kafka allows us to consume the PLC data, unpack and interpret them so that the data can be re-published back into Kafka, and become ready for further analysis. By delegating the data processing to standard PC hardware, we can currently process approximately 500,000 datapoints/s. Moreover, data collection and ingestion architecture of this case study is described in Sect. 4.

Furthermore, to gain access to the data in a structured manner, we utilized the CATCH.AI proprietary system. The system gives the ability to store, visualize, and act on the data in an easy-to-use interface, so the focus can stay on developing the analysis tools. Furthermore, the CATCH.AI system is used to set up a trigger for the data analytics model that is executed when a particular manufacturing process step is concluded. In Sect. 5, the details of the CATCH.AI tool are clarified.

The data analytics model deploys a machine learning method to extract the summarized knowledge from the database. In other words, to evaluate the quality of the products, an anomaly detection model is developed for one step of the assembly process. To train the anomaly detection model, some products in normal status are produced. However, to validate the detector, some fault injection experiments also need to be conducted. The quality and sample numbers also play an essential role in the performance of the model; therefore, some synthetic data are produced with a data augmentation method. Furthermore, Sect. 6 describes the experiments and machine learning methods that have been used in the case study.

This chapter describes our case study and introduces different definitions and elements. We will discuss about the novelty of this work, the physical system, the volume of the data, and the data analysis and processing tools. Finally, we discuss the challenges in enabling a DT of such a large case study, along with lessons learned and future work.

The remainder of the chapter is organized as follows. In Sect. 2, related work in DT for manufacturing is discussed. Section 3 introduces the physical system and the process of interest. Furthermore, the details about the data collection and storage tools that have been used in this case study are provided in Sect. 4. Moreover, Sect. 5 describes the dashboard and visualization tool, CATCH.AI and its connection to the data management section and the data analytics tool. Afterward, Sect. 6 presents the anomaly detection model and different assembly experiments to produce normal and abnormal products. Finally, Sect. 7 summarizes the chapter and discusses the challenges of constructing a DT for a manufacturing pilot line.

2 Related Work

In recent years, people in academia and industry have invested in designing DTs for various physical entities, which has led to different simulation tools employed for such physical machines. Data storage and transmission methods for further analysis have been explored concerning data with diverse volumes or content in various applications. Furthermore, DTs with diverse services have been developed for physical devices with different objectives. For displaying the results of the DT, various visualization tools and dashboards have been designed. This section introduces some of the DT enablers, tools, and techniques briefly.

2.1 Physical Systems

Designing DT has gained attention in different industries; therefore, various physical entities have been studied for developing DT. In [10], the authors defined an architecture for developing DTs and examined their proposed method in a case study which includes a refinery automation system with four valves. Moreover, some physical systems like grinding wheel [11], 3D printer [12], welding production line [13], rotating machinery [14], machine tools [15], and robots [16] have been invested for designing DT. In [17], the authors proposed an incubator system that is complex enough to highlight the need for DTs while at the same time being simple enough to be built from widely available tools. Later, in [18], the authors described the implementation of a DT for the incubator system. The resulting architecture has been generalized in [19] based on the comparison with another DT for a race car test bench.

2.2 Data Management Technologies

Data storage and transmission are data-related functionalities for expressing the physical entity and connecting it to its digital replica. Therefore, various methods have been proposed and applied for these purposes.

2.2.1 Data Storage

There are various frameworks for big data storage, for example, MySQL and HBase. In the MySQL framework, data are stored as tables with records of data in rows and the data description in columns [20]. Furthermore, for storing the data related to the machine tool in [15], the PostgreSQL database is employed. This database is an open-source database running on a local PC through the Internet using a script in Python.

2.2.2 Data Transmission

Different data transmission protocols have been introduced to efficiently and securely connect the two digital and virtual replicas. Lu et al. in [2] describe how industrial communication protocols have evolved from the fieldbus legacy communication method to the second generation, Ethernet-based protocols and the current category, wireless network technologies. All these improvements are implemented to satisfy the real-time and reliability requirements of industrial processes. On the other hand, transmission mechanisms can be divided into two categories wire-based or wireless methods. Some of the wire-based tools are twisted pair coaxial cable and optical fiber; the wireless methods are Zig-Bee, Bluetooth, Wi-Fi, ultra-wideband (UWB), and near-field communication (NFC) [10].

2.3 Digital Twin Services

Depending on the physical system, DTs have diverse objectives; for instance, in the aerospace domain, a DT should be able to predict the life cycle of an aircraft. However, the DT machining application enables real-time quality inspection of machining results [21]. Furthermore, one of the important yet less achievable goals of a DT is process optimization and control that is implemented for a machine tool to stabilize machining parameters for achieving optimum surface roughness in [22]. On the other hand, fault diagnosis is one of the DT services that has been implemented for different physical systems. For example, the authors in [14] developed a pilot digital twin prototype of a rotor system that effectively diagnoses rotor unbalance fault and predicts its progression.

3 Physical Pair

This section describes the physical system in this case study briefly. Moreover, different machine and the device components are shown and explained to better understand the process. The process of interest is briefly introduced since the anomaly detection model is designed for this process.

3.1 Pilot Line

The physical pair consists of a test bench for medical device assembly by Stevanato Group/SVM. As shown in Fig. 1, this small assembly line contains a base and top frame (1 and 2). The transport system (3) is a modular XTS linear motion platform by Beckhoff automation. The linear motors (5 and 6, Linmot PR02-52) provide both vertical and rotary motion and are equipped with force and torque transducers for continuous process monitoring with sampling frequencies up to 20 kHz. A sensor system (4) for single-point data is used to verify the assembly process. The most common way of doing so is by measuring the total height or other geometric dimensions of the assembly.

A closer look of the system is provided in Fig. 2. The mover, or pallet, is mounted on the transport system. It contains the sub-assemblies and component to be assembled and can move to an arbitrary position along its axis of movement.

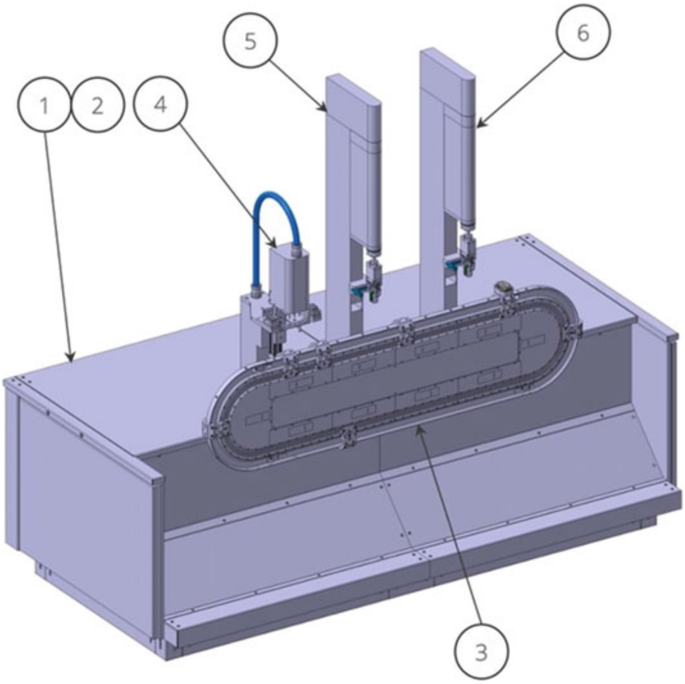

Fig. 1 Schematics of the physical pair while the actual machine is shown in Fig. 2. The assembly equipment consists of (1) base frame, (2) top frame (not shown in figure), (3) transport system, (4) sensor system, (5) and (6) linear motors. The linear motors perform the assembly steps, and the sensor system verifies the assembly

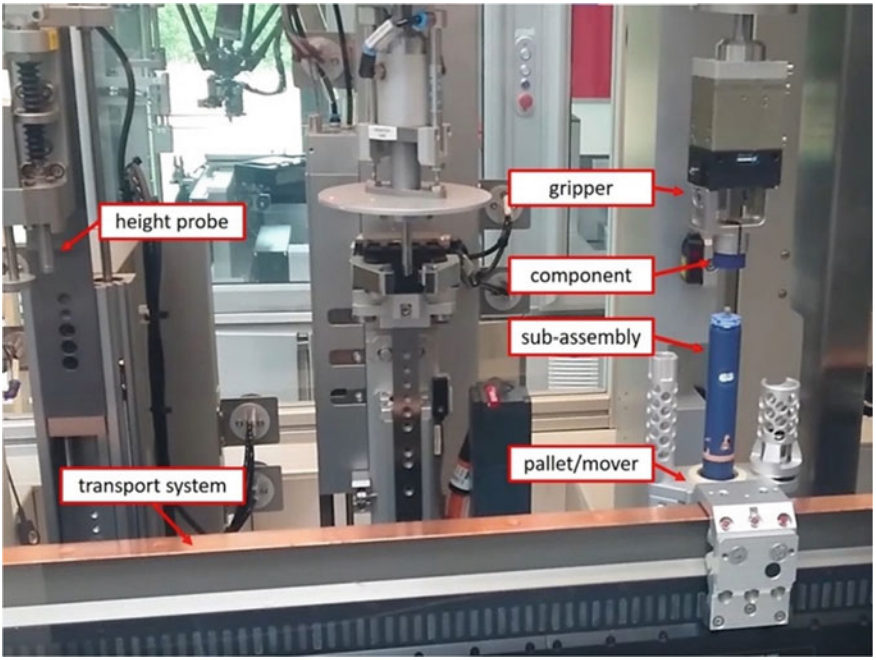

Fig. 2 A more detailed look at the equipment from Fig. 1. The transport system moves a pallet, also called mover, which contains components to be assembled. In this figure, a gripper, mounted on linear motor (6), holds a component which must be mounted to a subassembly for the fabrication of a device. Correct assembly can typically be verified by using a height probe

3.2 Process of Interest

The test case in this study is the assembly of a medical device. Its constituent components and assembly process steps are shown in Fig. 3. First, two modules, also called subassemblies, are mounted together (as shown in Fig. 3a). This requires linear movement in the direction of the arrow with prior alignment and rotational orientation along the long axis of the modules. Next, the modules are joined using a snap-fit consisting of two main snaps and two minor snaps to stabilize the assembly. A certain axial force is required for successful operation. Second, a similar process with a segmented ring snap is performed with a single component mounted onto the new subassembly (shown in Fig. 3b) to form the complete device shown in Fig. 3c.

A snap joint between two plastic components is illustrated in Fig. 4. Upon mounting the green component (moving right to left) onto the blue one, the entire snap structure is bent inward until the "hook" snaps into place and establishes the joint. The axial force mentioned above is needed to bend the snap structure and overcome friction during the assembly process.

According to the process sequence in Fig. 3, the mover is positioned, and the one subassembly is picked up by the gripper, which then moves upward. The mover is

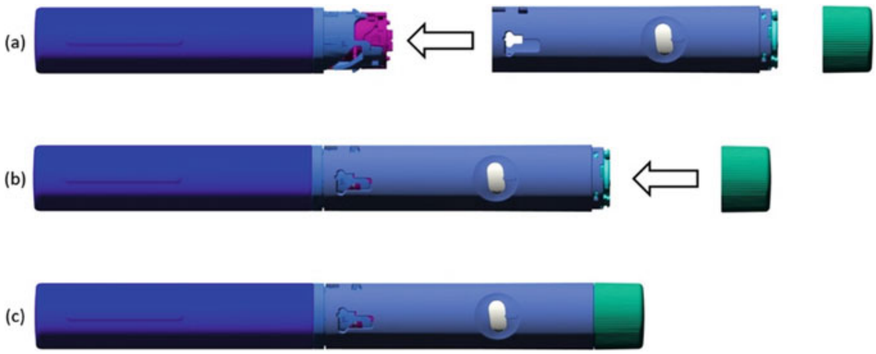

Fig. 3 Assembly of a medical device consisting of two modules (subassemblies) and one component (**a**). The two modules are assembled in (**b**), and the device is completed when the final component is mounted (**c**)

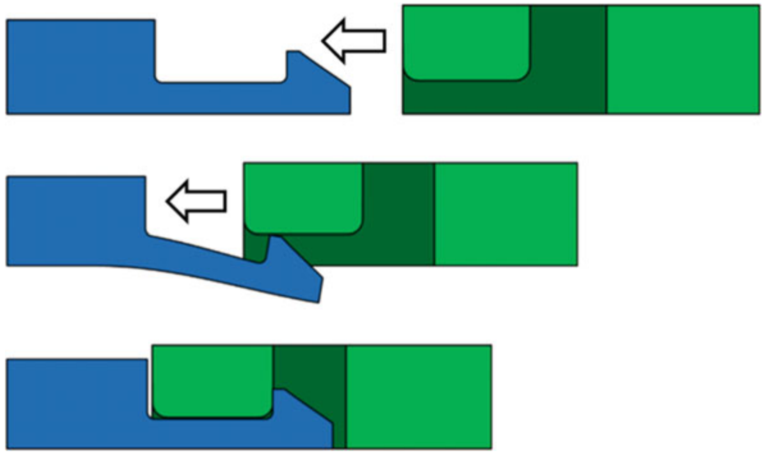

Fig. 4 Snap joint between two plastic components (image by Christoph Roser at AllAboutLean.com under the free CC-BY-SA 4.0 license)

then repositioned, and the two subassemblies are mounted by a controlled movement of the linear motor. This sequence is then repeated for the second step in which the single component is mounted to complete device assembly.

3.3 *Process Assessment*

The entire sequence is shown in Fig. 3. Both for the assembly process itself, as well as the axial acceleration and deceleration of the motor with the gripper, forces are required. The process is typically verified by a height measurement, which ensures that all components are assembled in the correct position. However, geometrical tolerances may cause the verification to be insufficient, and additional action is needed to ensure the snap quality is perfect.

One of the solutions that can address this problem is to correlate the product quality and the process behavior. In other words, by looking into the force and displacement curves that represent the process behavior, we can evaluate the quality of the products. For this purpose, a data transfer layer is needed to collect the data and store them on a hard drive for data access and visualization.

4 Data Management

In this section, the data collection and storage methods are briefly described. First, the data transfer layer Apache Kafka, a distributed event store and stream-processing platform applied for data collection, is explained. The data transfer layer runs on a local computer close to the physical system. Then, data are temporarily stored in Kafka, and later, it can be transferred to a cloud-based solution.

4.1 Data Collection

Extracting data from PLCs in real time and with a resolution sufficient to capture all state changes requires a very efficient data collection mechanism. In order to collect and harmonize the data coming from the different PLCs of the manufacturing line, an Apache Kafka-based data collection platform has been implemented.

Kafka is chosen as a transport layer in the solution due to its unique capabilities for high throughput and strict ordering guarantees. Furthermore, Kafka is well supported and integrated into standard data engineering and analytics tools and therefore provides a bridge between the industrial engineering traditions and modern data science development methodologies.

The platform consists of a number of input adapters (Kafka Connect sources) that consume a continuous stream of binary data from the PLCs that are optimized for transmission efficiency and publish them into a separate Kafka topic for each PLC. The binary data are then consumed and converted into a structured format and published back into new topics ready for further consumption by data analytics tools as shown in Fig. 5.

In our setup, the input adapters support two commonly used protocols, MQTT and plain TCP. The data format transmitted through these protocols is typically not standardized, and therefore, the interpretation/conversion into a structured format is tightly coupled to this format.

Many solutions for consuming process data generated by PLCs rely on sampling-based technologies like OPC-UA where the current state of the PLC is sampled at

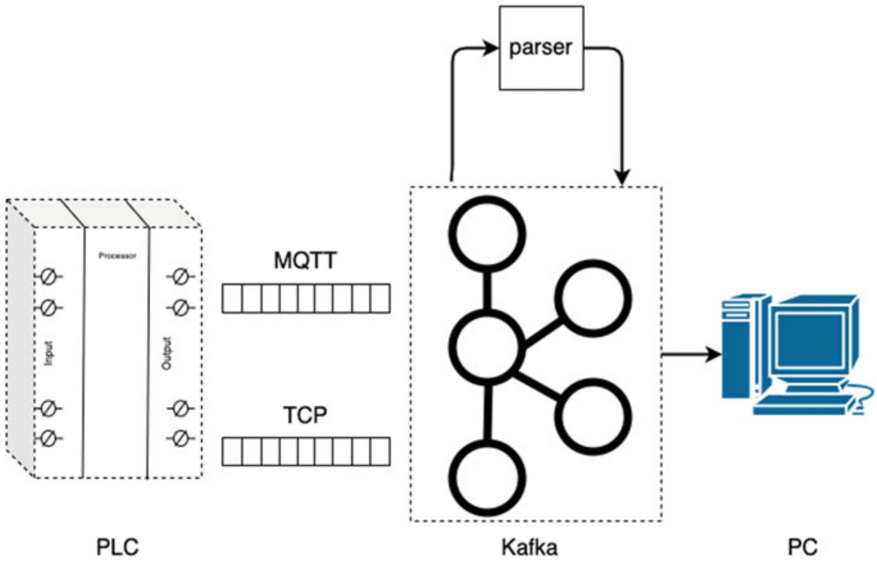

Fig. 5 Data collection structure with Kafka

regular intervals, typically every 100 ms. This is often sufficient to capture high-level process steps, but not always enough to fully create a model of the physical system. Therefore, the PLC code has been augmented with a block that during each scan cycle transmits all changed data values to the Kafka input adapters.

4.2 Data Storage

Kafka supports the concept of automatic retention management. That is, each topic containing data in Kafka can be configured with a retention parameter telling Kafka for how long to store data in the topic. This is used to allow Kafka to take on the role of a data buffer. Data are typically stored in Kafka for hours or a few days in which time-relevant data are retransmitted to more permanent data storage, e.g., an SQL database or a cloud-based system.

5 Dashboard CATCH.AI

In this section, CATCH.AI, the dashboard and visualization tool, is briefly introduced. CATCH.AI is a flexible software solution made for working with significant amounts of data. The data model structure, dashboard, and some CATCH.AI capabilities are explained in the following. It is outside the scope of this chapter to give a full overview of CATCH.AI features. We refer the reader to [23] for more details. In the following, we discuss the features of CATCH.AI used in connection to the case study.

5.1 Catch.AI Overview

Catch.AI is a tool that allows the creation and configuration of dashboards, visualizations, data collection, and feedback loops that can reconfigure the physical system. Figure 6 shows an example dashboard, where the time series related to a process and different diagrams related to it are displayed. However, CATCH.AI cannot use data analysis tools internally; it can activate external sources for data analysis purposes.

CATCH.AI is made as a flexible solution that can cater to a wide range of different inputs; in this case study, we will focus on the input from the Kafka system. The raw data are transferred from the Kafka database to the CATCH.AI data model. It provides an easy-to-use Web interface that makes the data accessible event based. Furthermore, the report section in CATCH.AI makes it possible to access historic data for data mining purposes. In addition, CATCH.AI provides dashboard functionality with both historical and live data.

5.2 CATCH.AI Connection to Kafka

CATCH.AI has a REST API with OPENAPI3 description available. This interface is used to connect Kafka and CATCH.AI. A custom mapper application is made for the project to take care of the Kafka consume interface and map it into the domain model of CATCH.AI. This mapper also ensures that we have more clean data to work with, since NULL characters can occur in the raw data streams. Therefore, the data are cleaned up before being made available in CATCH.AI for easier usage by the end-user.

5.3 CATCH.AI Data Structure

As mentioned above, CATCH.AI organizes data in an event-based manner to make it easier to access data related to different steps of product assembly. Therefore, labeling the data with three keywords: **device**, **event**, and **property,** enables an easy access method to reach the data with specific characteristics.

The different equipment in the physical system or the DT correspond to the keyword **device** in our case study; for example, the linear motor, shown in Fig. 1 as number (6), in the assembly line is addressed as one device in CATCH.AI.

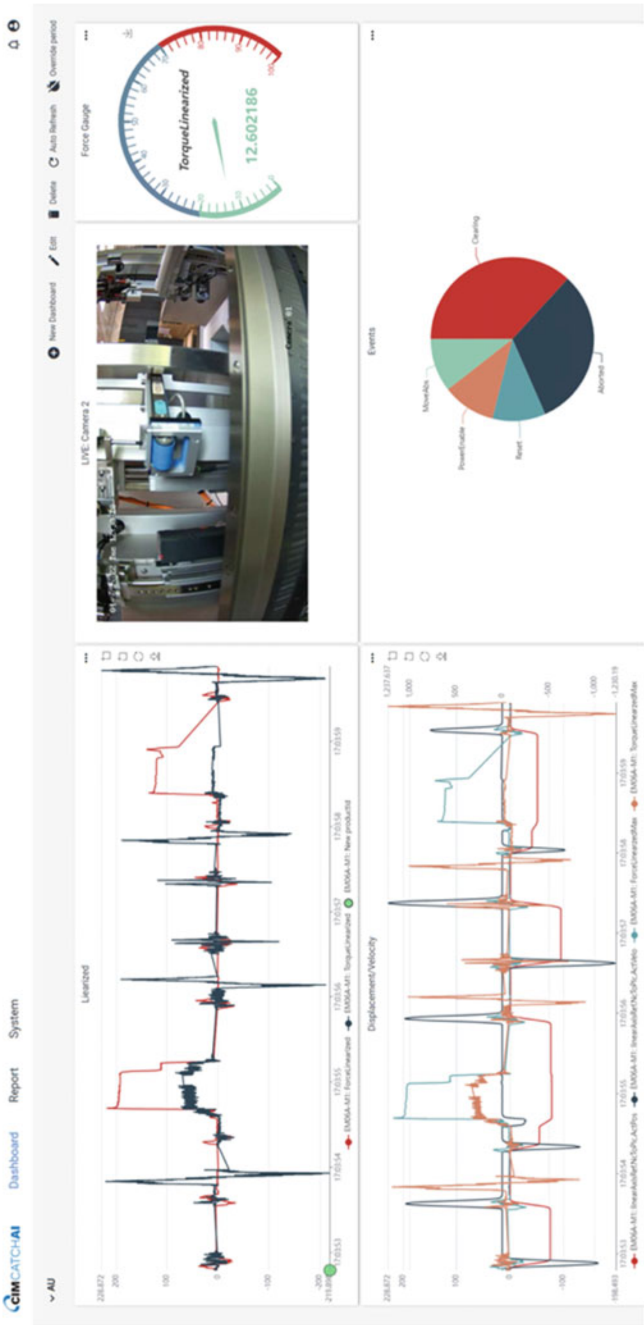

Fig. 6 CATCH.AI dashboard. The plots in the left show EM06-M1 (device) properties (force, torque, and displacement) related to one product assembly, while the camera shows the live video of the assembly process. The diagram in the right bottom corner shows different events in the product assembly

Furthermore, the **property** of a device is defined as measurement values or states related to the device; for example, the force sensor in the linear motor is defined as a property.

Moreover, different state changes in properties of the machine form **event**. For example, the stop and start points in producing a product can be defined as events (see Fig. 6). However, different events can be described based on different properties.

In this case study, the process of interest (as described in Sect. 3.2) is defined as an event base on the displacement as the property and the linear motor as the device. Therefore, it is easier and significantly faster to access the data related to the process of interest.

5.4 CATCH.AI Data Access

The event-based data structure lets the end-user access the specific data in the timeline of the assembly process. On the other hand, if the end-user wants to access the data related to one unit in production, they can select two events, "Start Process" and "End Process."

Therefore, the advantage of describing the data structure based on events is that it makes it possible to search a significant volume of data from weeks of production, including billions of data points in a short period. For example, Fig. 7 shows data related to a unit produced in the assembly process. Different properties of Device 1 regarding starting and ending events are visible there.

5.5 CATCH.AI for External Services

Instead of polling for data in CATCH.AI on an interval, the system also contains the "RuleEngine," allowing us to work directly with the stream of data. For example, the RuleEngine can be set up to trigger an external process when the product is finished. In this case, later additions to the system, such as machine learning algorithms, reporting, and other visualization tools, would not necessarily have to parse everything in real time, but only act when required, that is, when a specific pattern is found within the data stream.

In this case study, the data related to each product assembly process can be transferred to the anomaly detection model via CATCH.AI by triggering the corresponding Python code. Figure 8 shows the rule management system in CATCH.AI where the anomaly detection model is triggered when the product assembly is finished.

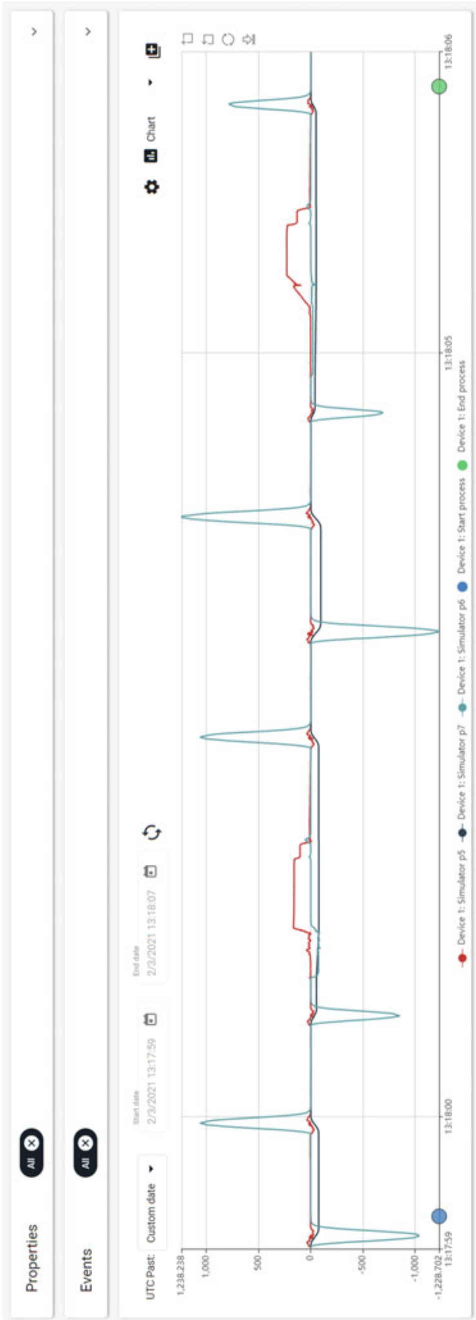

Fig. 7 Access history data in CATCH.AI showing Device1 all properties and events

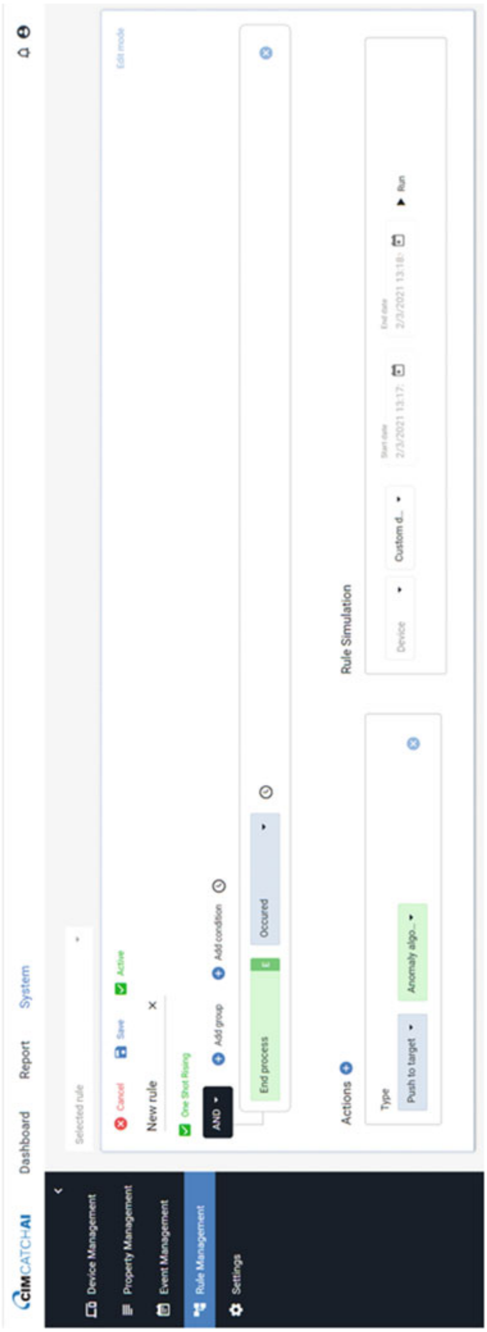

Fig. 8 Rule management system in CATCH.AI

6 Anomaly Detection Model

In this section, the anomaly detection model is described. This includes the machine learning model, the dataset, and the experiment settings used to train and test the anomaly detection model.

6.1 Product Quality Assessment

Evaluating the quality of products in an assembly process is critical. In this case study, we evaluate the products by analyzing the behavior of the assembly process, which is equal to looking into various signals from different parts of the process and using this to predict the product quality. Anomaly detection also is a process monitoring tool for early warnings before the product quality is compromised.

This case study is a proof of concept. It is essential to evaluate the process quality based on the recorded signals. Figure 9 shows the force and displacement recorded over the time from one of the equipment in the pilot line. The highlighted area in Fig. 9 shows the force and displacement curves in the process. The force profile is the measurement we investigate since it records the force applied to assemble the components and the reaction.

The aim of analyzing the force profile is to find the anomaly in the products via signals recorded while producing the product. For example, Fig. 10 shows that the abnormality can be visible with the force signal by plotting the force curve related to a normal and abnormal product in the same image. The blue signal was recorded

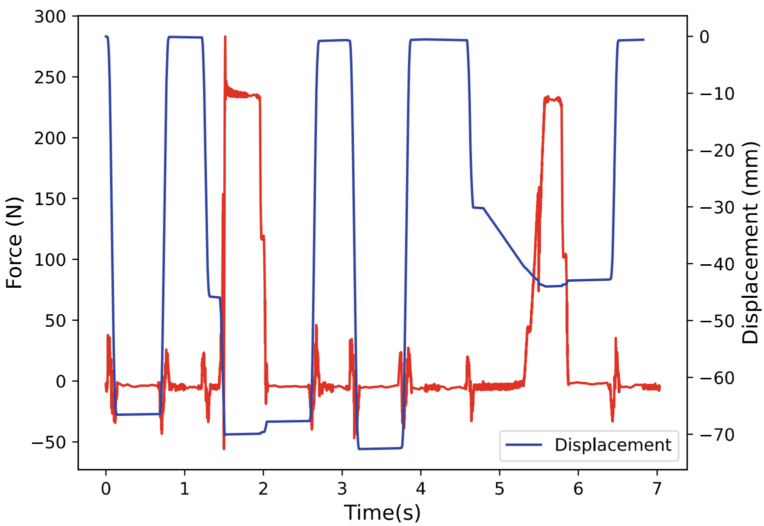

Fig. 9 Force and displacement of the process

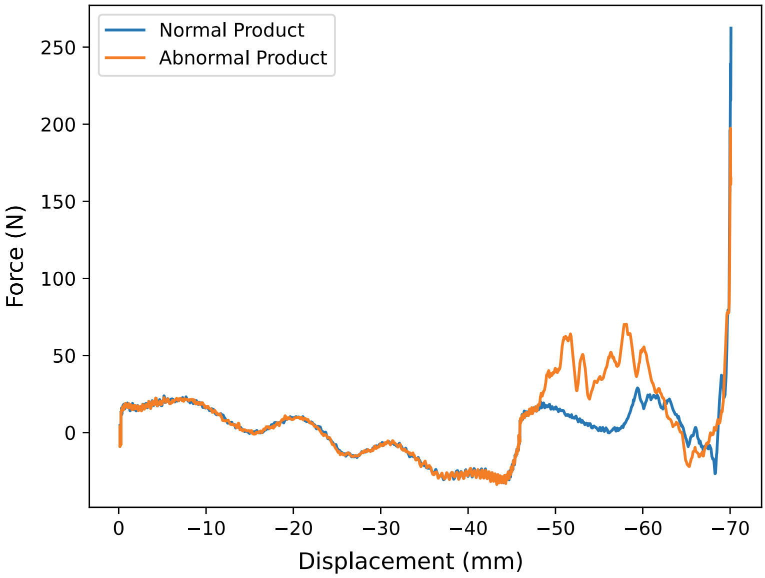

Fig. 10 Force–displacement for normal and abnormal products

when a normal product was assembled; while the orange one displays an abnormal product that deviates from the normal status.

An anomaly detection model should be developed to detect the anomalous cases automatically based on the deviation from the normal situation. Since anomalies can rarely happen, mining the signals related to normal products is valuable. We want to identify the outer bounds of the normal date such that data outside this limit can be classified as abnormal concerning what is considered normal data.

6.2 Detection Model

The detection model consists of a one-class support vector machine (OCSVM) [24] to find the boundary enclosing the normal data and random guided warping to generate augmented data. The augmented data can help generalize the detection model and improve performance. Below, the theory related to these methods is described briefly.

6.2.1 One-Class Support Vector Machine

To detect the abnormality in the force curve, the OCSVM model is applied. This method is trained by using only normal data, which is mapped to another feature space through a nonlinear kernel function. In that feature space, the objective is to define

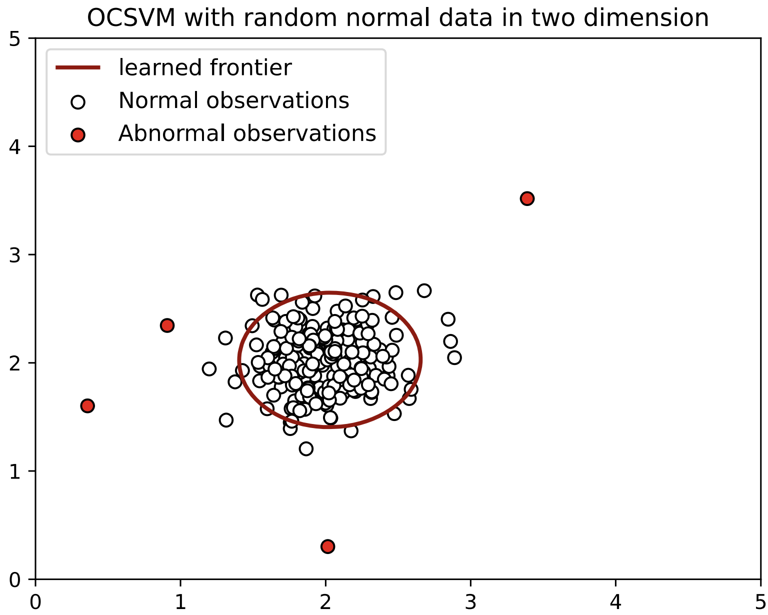

Fig. 11 Finding the boundary around the normal data with OCSVM for a random dataset in two dimensions

the hyperplane that best discriminates this data from the origin. This hyperplane in the feature space then corresponds to a complex shape in the original space enclosing the normal data.

For example, as shown in Fig. 11, the white and red dots show normal and abnormal random data points, respectively, in two-dimensional space. With the help of the radial basis function (RBF) as the nonlinear kernel, the boundary around the normal data can be calculated in a way that does not include the abnormal data (for more information about the theory, see [24]).

With adjusting the boundary, the accuracy of the model can be increased, or it can worsen the performance of the classifier, as shown in Fig. 11. Therefore, introducing a penalty term weighted by ν in the optimization formula as the regularization factor can express the trade-off between model complexity and training error; ν controls the number of training samples excluded by the decision boundary.

In Fig. 12, the normal training samples (white dots) are used to train the OCSVM. The abnormal data (red dots) and normal test samples (green dots) are used to evaluate the performance of the model. Figure 12 shows that increasing ν tightens the boundary and does not allow anomalous samples. On the other hand, a smaller ν will introduce some uncertainty in training dataset. Therefore, tuning the hyperparameter ν is an essential factor in training OCSVM to gain the suitable performance at test time.

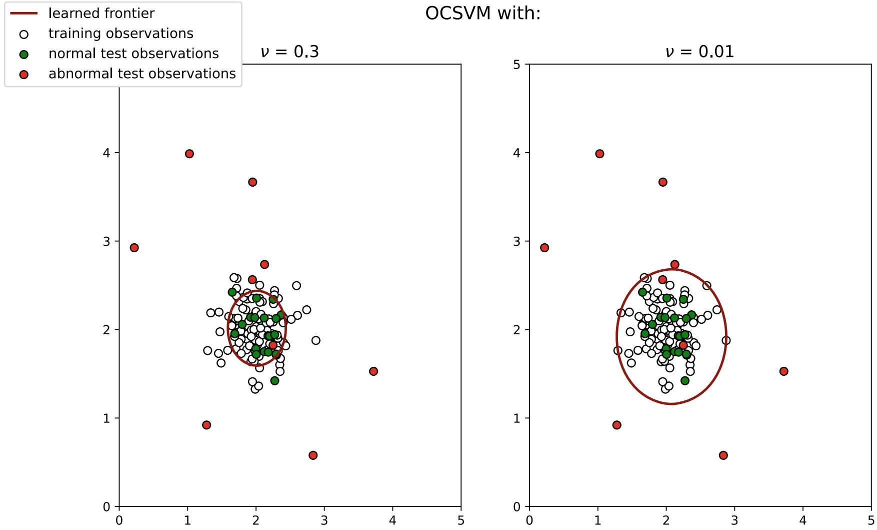

Fig. 12 OCSVM performance with different ν values

6.2.2 Data Augmentation Method

Random guided warping is applied to generate new normal samples to address data shortage [25]. The backbone of this method is a similarity search technique called dynamic time warping (DTW); this augmentation algorithm can generate new data similar to the real dataset.

Dynamic Time Warping

DTW is a classic method for finding the optimized distance between two time series, and it is robust to temporal distortion. Consider two time series $\mathbf{r} = r_1, \ldots, r_i, \ldots, r_I$ and $\mathbf{s} = s_1, \ldots, s_j, \ldots, s_J$ with sequence lengths $\boldsymbol{I}$ and $\boldsymbol{J}$, respectively, shown in Fig. 13. We consider $\boldsymbol{r}$ and $\boldsymbol{s}$ to be univariate time series. To find the global distance, DTW finds the minimal path on the element-wise cost matrix C (the Euclidean distance) using dynamic programming (for more information about the theory, see [26]). Furthermore, the two sequences are stacked in Fig. 13 with a bias to see the warping path.

This minimal path is referred to as the *warping path,* and the warping path is a mapping from the time steps of one series to the other. For example, the gray lines in Fig. 13 show the warping path. However, instead of using a one-to-one mapping from two time-axes in series, similar patterns are connected to find the optimum distance between **r** and **s**.

Random Guided Warping

Random guided warping uses DTW and a reference pattern to generate synthetic patterns. In this case, instead of randomly warping the data sample and hoping it is

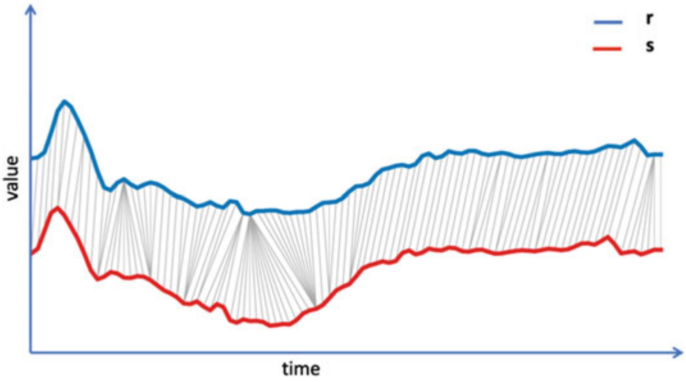

Fig. 13 Alignment with DTW between $\boldsymbol{r}$ and $\boldsymbol{s}$ [8]

realistic, a teacher is used to instruct warping in time domain. For example, assume $\boldsymbol{S} = \{\boldsymbol{s}_1, \boldsymbol{s}_2, \ldots, \boldsymbol{s}_N\}$ is the training set, an augmented dataset will be generated called $\boldsymbol{S}'$ such that the accuracy of anomaly detection model trained on $\boldsymbol{S} \cup \boldsymbol{S}'$ is better than $\boldsymbol{S}$ alone. One of the advantages of using a reference for warping is that both the local patterns exist in the original dataset.

For generating an augmented sample $\mathbf{s}'$, a *random* sample $\mathbf{r}$ is chosen from the training set $\boldsymbol{S}$. Furthermore, the warping path between two data samples $\mathbf{s}$ and $\mathbf{r}$ can be calculated by DTW. Moreover, we can exploit the warping path to align the elements of the two time series. By aligning the elements in this way, sections of $\mathbf{s}$ are warped in the time domain to fit $\mathbf{r}$ as shown in Fig. 14.

The result is a sequence $\mathbf{s}'$ that has the feature values of $\boldsymbol{s}$, but the time steps of $\mathbf{r}$ under the warping path constraints provided by DTW. Finally, the process is repeated by selecting any two random patterns in $\boldsymbol{S}$. It is possible to synthesize N^2 number of time series where N is the number of patterns in each class $\boldsymbol{S}$. Finally, the augmented training set $\boldsymbol{S}'$ and the real training set $\boldsymbol{S}$ train the anomaly detection model, as shown in Fig. 14.

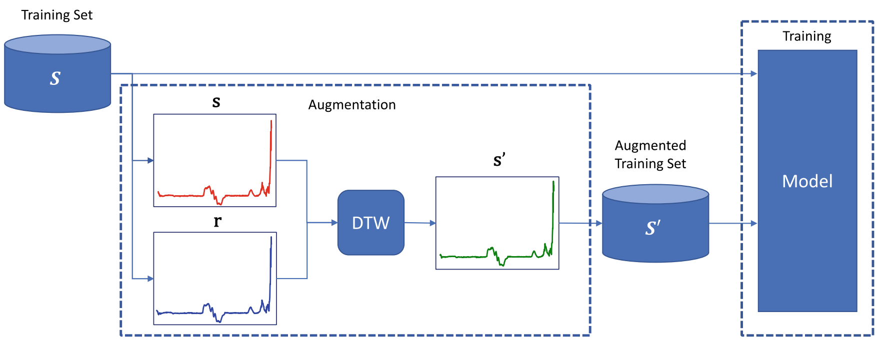

Fig. 14 Random guided warping for generating $\boldsymbol{S}'$ (inspired by [25])

Table 1 Different types of faults that have been applied

Type	Value	Product ID
Type 1	175°	8
	170°	9
	185°	10
	190°	11
Type 2	4	19
	2	20
	2	21
	3	22
	All	23

6.3 Experiments

Some experiments have been operated to collect data related to abnormal products, which is described in the following. Furthermore, a normal dataset is introduced in this subsection for training the model and is collected by running the physical system in the regular setting. For tuning the hyperparameter ν, the normal and abnormal data are split into train, validation, and test sets, which is described in detail in this subsection.

6.3.1 Fault Injection

Some data samples with abnormal labels are needed to test the anomaly detection model. However, the process is robust, and the probability of an anomaly happening is low. Therefore, many products need to be assembled before an anomaly occurs. However, producing many products with the pilot line is costly. Therefore, we had to introduce some fault into the process to test any future anomaly detection method. For this purpose, two types of faults have been applied.

- **First Type**: With this type of fault, the setting related to the gripper position is changed (see Fig. 2). The default setting is 180°, but we gradually changed the default setting with ±5° and ±10° according to Table 1.
- **Second Type**: With this type of fault, we remove some of the deformation structures of a plastic component in the product. Different number of components have been removed, as Table 1 shows.

6.3.2 Dataset

For training and testing the anomaly detection model, data samples with labels *normal*, *abnormal* are needed. Therefore, 102 devices were produced in normal situations, and force measurements related to these products were collected. These

Table 2 Dataset description with normal and abnormal labels

Data type	Number of samples	Time series length
Normal	102	11,239
Abnormal	9	11,299

force samples are referred to as normal data through this report. Furthermore, nine abnormal devices were assembled to test the anomaly detection model (see Table 1). Therefore, the data related to these abnormal devices are addressed as abnormal data.

Table 2 shows the normal and abnormal dataset and the time series length. The size of normal and abnormal dataset is one of the challenges in this case study; since producing the products is expensive, we relied on a small database. However, to overcome data shortage, we use a data augmentation method (see Sect. 2).

6.3.3 Hyperparameter Selection

For finding the boundary around the normal dataset, the OCSVM model is applied according to Sect. 6.2.1. In this model, the RBF is the kernel for mapping the raw data to a new feature space; therefore, tuning the hyperparameters ν in OCSVM is a vital task.

For tuning ν, we used a five-fold cross-validation method that can consider the anomaly data in the validation time. Values in $[0.001, 0.01]$ have been investigated with a step length of 0.001 to find the best value for ν.

For conducting the cross-validation process, the normal data are split into train and test sets with the ratio of (80%, 20%). In each iteration of cross-validation, we split the training set into five subsets which four subsets are used for training the model while the remaining subset is used for validation.

Furthermore, Fig. 15 explains how the five-fold cross-validation process is applied. The training set formed by only normal data is split into five subsets. For each candidate value of ν, we apply five experiments as follows. On each experiment, we use four (out of the five) subsets to train the model. The remaining subset is merged with the abnormal data (four samples) to form the validation set. We train the OCSVM with the training set (formed only by normal data), and we evaluate its performance on the validation set (formed by both normal and abnormal data). After running the five experiments, we calculate the average performance. Then, the average performances corresponding to different values of ν are sorted, and we select the value of ν corresponding to the best performance.

As shown in Table 3 for different values of ν, the performance of the model differs. In this project, the F1-score ($2\frac{\text{Precision}\times\text{Recall}}{\text{Precision}+\text{Recall}}$) is the metric used for choosing the best model; the OCSVM model with a higher F1-score is selected. For example, among (0.002, 0.001) with the highest F1-score, we set up ν to 0.002.

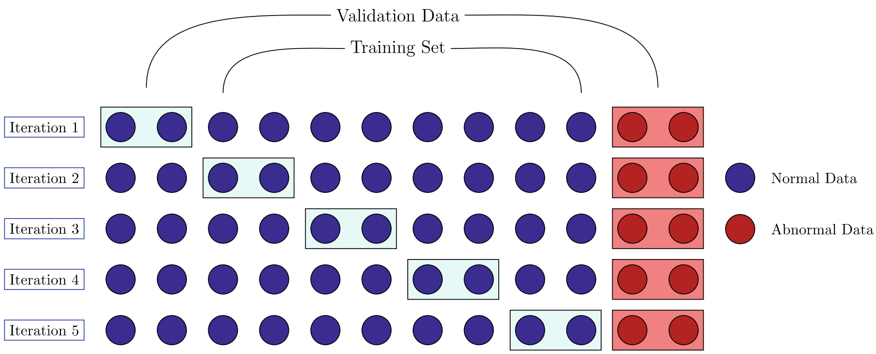

Fig. 15 Five-fold cross-validation. normal validation

Table 3 Results of the cross-validation for finding the hyperparameter ν

ν	F1-score
0.01	0.8975
0.009	0.8975
0.008	0.8975
0.007	0.8975
0.006	0.8975
0.005	0.8975
0.004	0.9006
0.003	0.9006
0.002	0.9041
0.001	0.9041

6.3.4 Results

The result for the OCSVM with the augmentation method is shown in Table 4. The five-fold cross-validation algorithm employs the normal and abnormal data as the train and validation set for tuning the hyperparameter for the OCSVM. As described in Sect. 6.3.3, in each iteration in the cross-validation, four subsets of data are used for training. The fifth subset of data is chosen to validate the model with specific ν. The last 20% of the normal data are reserved for testing the final anomaly detection model.

Table 4 Results of the anomaly detection model

Result/model	OCSVM	OCSVM with Random guided warping method
F1-score	0.67	0.89
Recall	1.0	1.0
Precision	0.5	0.8

Table 4 shows the results of the anomaly detection model with test set that includes 20% of normal data and five anomalous samples. We used the data augmentation method to improve the performance of the model. The results in Table 4 indicate that augmented data help improve the model performance by generalizing the model.

The OCSVM, with the assistance of augmented training data, can define a boundary around the normal samples; therefore, the abnormal products can be successfully labeled by testing the force measurements recorded while assembling them with the anomaly detection model.

7 Conclusion

This case study aims to establish a DT for a physical system, trace back the anomalies to the leading source, and predict the quality of the products with more confidence, higher speed, and less invasive methods. Moreover, the DT can help the operators by visualizing the signals related to the assembly process. In this case, they better understand the process and the machine.

This chapter discussed developing a DT for a medical device assembly pilot line. First, we described the physical machine and the product in detail and clarified the process of interest where we focused on developing the machine learning tool. In the process of interest, the subassemblies are mounted together with vertical displacement and applied force. The critical point in the process is the snap process quality, where two components should engage precisely.

Second, we introduced the Kafka data ingestion tool to collect and store data locally for further analysis. In this case, the binary data are collected through PLCs via Kafka with efficient speed and then consumed and converted into a structured format and published back into new topics ready for further consumption by data analysis tools.

Then, we presented the CATCH.AI as a tool for creating and configuring the dashboard, visualization, and feedback loop that can reconfigure the physical system. In addition, CATCH.AI can organize the data collected from the physical system, make it easily accessible, and trigger the external data analysis tools for data mining purposes.

Eventually, we introduced the anomaly detection model and the experiments we conducted to assemble the normal and abnormal products. First, we applied a one-class support vector machine model to determine the boundary around the normal data. To make the model generalize better, we used an augmentation algorithm to widen the decision boundary. The anomaly detection model is reliable, and we can apply a similar model to detect abnormal samples in the other steps of the assembly process.

One of the challenges in this case study has been collecting a large amount of data from different assembly process steps with high throughput and low latency, storing the data in a structured way and mining a large amount of data. Therefore, to overcome these challenges, we propose different solutions; the Kafka data layer can collect the data with high throughput and store the data locally. However, a cloud-based storage solution will be considered a permanent solution. Moreover, by focusing on one assembly step at a time, we split the big data mining problem into smaller subproblems; therefore, we analyzed a smaller volume of data to extract the knowledge.

Acknowledgements We would like to thank the following people from Novo Nordisk A/S; Jeppe Wind, Tinna Dofradóttir, Thomas Algot Søllested, and Sebastian Dengler for providing the physical system, conducting data collection, and insights to understand the assembly process.

Additionally, we extend our gratitude to Novo Nordisk A/S, CIM Industrial A/S and Alexandra Institute A/S for their participation in this case study.

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An Architecture for Intelligent Agent-Based Digital Twin for Cyber-Physical Systems

Hussein Marah and Moharram Challenger

1 Introduction

Digital Twin is one of the cutting-edge technologies in the era of smart production and manufacturing of the fourth industrial revolution (Industry 4.0), where cyber-physical systems (CPS) and the Internet of Things (IoT) are pervasive and widely utilized, and they play a major role to realize such technology [1]. Digital Twin has been considered a powerful and promising technology that can be utilized in multiple phases of the CPS product life cycle (e.g., designing phase, implementation phase, production phase, and evaluation phase) by utilizing the bi-directional data communication between physical and digital worlds. Digital Twin has gained much attention in the last decade from the research community and the industry as well.

According to several definitions of the Digital Twin, it can be defined generally as a replica of a physical system and its assets that are connected to and which are being represented in a virtual world which wraps all the desired properties and features that represent how the real physical system is interacting with the environment [2]. Digital Twin usually collects data from sensors of the physical system, which might be stored in a cloud or a data repository (e.g., a database). The Digital Twin can use the stored data to perform specific tasks like analysis, diagnosis, forecasting, and visualization to evaluate the performance and check the system's behavior.

Despite the significant potential and promising applications of Digital Twin, engineers face numerous challenges when building and modeling Digital Twins. The process of creating an identical virtual representation of a physical system comprises several challenging tasks, such as dealing with the real-time data that is sent from

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_3

the physical systems and making this data available instantaneously to the digital representation—also tackling the different levels of complexity in the CPS where several heterogeneous components are connected and interacting with each other at different levels of abstraction. Modeling and deploying a Digital Twin depend on several requirements to produce a reliable and valid digital replica, especially for time-critical systems where the system's behavior and correctness must be ensured in a real-time frame, which verifies that the system operates correctly and adheres to its requirements.

Moreover, to model and design a trustworthy Digital Twin, we must use an approach that can deal individually with the different levels of complexity. The complexity that confronts engineers while designing and modeling a Digital Twin for a CPS should be tackled by intelligent techniques and approaches. For this matter, we suggest using the intelligent multi-agent system and agent-based modeling approach to achieve this goal, which can provide us with the required capabilities to model, design, and operate a Digital Twin.

Generally, computer modeling and simulation is a field that tries to imitate and emulate real-world objects or processes and their dynamics. Also, modeling and simulation can target the system planned to be built and represent it as a computational model to do tasks such as analysis, observation, and inspection to derive predictions, obtain an in-depth understanding of the expected system, and enhance its performance. The term "model" has several definitions in the literature, but in brief, a "model" is a simplified and abstract representation of real-world objects [3]. Modeling and simulation tools and frameworks are widely available due to the excessive demand to build and virtualize many systems to enable analyzing and observing physical objects even without their actual existence and in order to cut off the high costs of building physical systems in the absence of detailed information and having obscurity regarding their expected behavior [4]. Agent-based modeling and simulation (ABMS) is a subfield and an approach for modeling and simulation which first applied and recognized in different scientific areas, such as in biology, and ecology economy, where it was used to model and simulate complex phenomena and then was extended and applied in more disciplines, especially in STEM (science, technology, engineering, and mathematics) domain. Nevertheless, agent-based modeling has been applied widely in computer science domain [3].

This book chapter introduces a novel approach for designing and modeling a Digital Twin based on intelligent agent-based modeling and simulation. The term "intelligent" is sometimes ambiguous and can be interpreted and perceived differently according to the environment and context. Intelligence in the agent-based paradigm can be defined as the goal-directed behavior of agents, or in other words, the autonomous and reactive behavior of agents where they sense the environment and act accordingly to changes instantly, so they achieve their objectives. In addition, intelligent agents must show proactive behavior, such as taking the initiative to satisfy their predefined objectives and goals. Additionally, another essential feature in intelligent agents is their sociability, which governs the capability of interacting with other agents regardless of their type, location, or internal goals. Eventually, they can establish cooperation and coordination to achieve the common objectives of the entire agent system [5].

The remainder of the book chapter is organized into six sections as the following: Sect. 2 discusses the related works and existing studies in the literature. Section 3 paves the way by discussing the main paradigms, concepts, and definitions of the terms that are used in this chapter, such as intelligent agents and multi-agent systems, agent-based modeling and simulation, and Digital Twin. The proposed architecture was discussed in Sect. 4 at a high level, where the primary components of the architecture are explained and detailed. Section 5 gives a reference implementation and an overview of the technologies available to realize all the components in the architecture. Section 6 demonstrates a case study and discusses the tools and framework that are used to realize the system. A summary is given in Sect. 7, which summarizes the main points; also, questions and challenges are discussed; and finally, future works are briefly discussed and recapped.

2 Related Work

Many researchers have adopted agent-based modeling and multi-agent systems paradigms to develop and build robust and intelligent solutions capable of handling complex systems and their interactions [6]. The use of multi-agent systems to create cyber-physical systems has received notable interest from the research community; also, companies have developed and deployed many industrial agent-based solutions.

In the context of building a Digital Twin, which mainly mirrors the physical asset with their equivalent virtual entities (digital asset), the first step in this phase is to collect information about the components in order to be able to represent and visualize them digitally. Following this context, dealing with CPS could trigger several challenges due to the complex structure and the components' heterogeneity of the CPS systems. In this respect, researchers have presented, introduced, and discussed several and various methods, techniques, and architectures to tackle CPS-related challenges and tried to address the complexity that comes with these systems. In the literature, plenty and diverse approaches and methodologies are introduced, which mainly discuss about realizing and implementing Digital Twin. In this section, we try to summarize and concise some of these studies and works.

The authors in the paper [7] proposed a new DT modeling architecture. This architecture includes five layers to manage the data in the Digital Twin. Those layers are listed as the following (device layer, user interface layer, web service layer, query layer, and data repository layer). Also, in addition to the developed Digital Twin, an augmented reality system was created and used to display real-time information.

Haag and Anderl [8] built a Digital Twin of a bending beam test bench that combines specific modeling and simulation methods to simulate the physical entity, digital entity, and the connections between them.

The paper introduced in [9] presents the followed steps and procedures of constructing a Digital Twin for a mechanical machine called (sheet metal punching machine) to support the interactive design of optimal numerical control (NC) machining programs. Based on the results, the developed prototype could provide an interactive simulation for the basic behavior of the actual sheet metal machine, such as its machining operations, movements, and its connection with the robotic arms.

The research carried out by [10] introduced an architecture reference model for Digital Twin for cloud-based CPS. The main properties of this model help to identify the degree between interaction of basic and hybrid modes (computation, communication, and control). In order to realize the implementation, a smart interaction controller based on a Bayesian belief network was designed. The integration of the fuzzy rule base with the Bayes network enabled the system to make reconfiguration. To show the efficiency of the architecture reference model, the authors presented a telematics-based prototype for an application of driving assistance.

The paper [11] introduced the implementation of Digital Twin for the micro-punching machine system. Also, the paper discusses the key enablers for twinning the two assets (physical parts and their virtual counterpart). According to the results, ultra-high accuracy of punching and high-speed punching could be achieved in this implementation.

In [12], Zongmin Jiang et al. claim introducing a novel approach and a new reference that overviews practical applications of a Digital Twin. In their implementation, they present a model of Digital Twin body (DTB) named the OKDD model that constructed from ontology-body (OB), knowledge-body (KB), data-body (DB), and digital-portal (DP). Those models are applied to an example of a power grid substation. In addition, they provide a demo of the health management (PHM) system of a 110 kV substation.

Despite different Digital Twin implementations, there is a shortage of utilizing the agent-based modeling and multi-agent paradigm as core technology. In the next paragraph, we summarize related works that adopted agents as the core component to build Digital Twins.

In the research work that was proposed by [13], the authors developed a Digital Twin using a modeling method based on a multi-agent architecture. The paper focuses on specific objectives such as controlling and observing the quality throughout manufacturing processes. Additionally, it offers methods for collecting pertinent data, so it is possible to examine the corresponding effects and influences on the final product's quality.

A recent paper proposed in [14] discussed an approach to develop a Digital Twin of a plant (wheat). The plant is built as an intelligent system considering the knowledge base on macro-stages of plant development. The multi-agent methodology is used to monitor and control the development of the plant in many details.

The study in [15] proposed an approach that addresses one of the smart cities' issues. The authors exploited an existing simulation model of the traffic system in Hamburg City, and they presented an experimental setup to integrate the existing city's simulation model with a real-time sensor network. Then, by using a large-scale multi-agent framework named (MARS), a Digital Twin was built. The entire process defines the description of the model phase to the phase of retrieving the real-time data from the IoT sensors. Finally, an integration process for the existing simulation was presented and discussed.

In recent work, the authors in [16] proposed an intelligent agent-based architecture to increase the robustness of the Digital Twin, which includes improving the real-time synchronization and the accuracy of the representativeness in the DT. Secondary cryogenic manufacturing use case was used in this work.

In [17], intelligent Digital Twin architecture for cyber-physical production system (CPPS) is highlighted. In addition, the required components for the Digital Twin are also proposed; the paper considered two use cases such as self-x, plug and produce, and predictive maintenance. The authors of this paper required three main characteristics to realize a Digital Twin: (real-time data source from the environment, the ability to synchronize with this data and with the physical asset, and the capability of visualizing and simulating the acquired data). The implementation utilized some methods like anchor-point-method as well as an agent-based method for integration and dealing with the heterogeneous data.

A Digital Twin that is implemented in a cyber-physical manufacturing systems (CPMS) using the multi-agent paradigm utilizing the RFID technology is proposed in the study [18]. The objectives of the implementation are to improve tracking and tracing of the complex manufacturing processes. This study considered the interactions between both in a single system itself and the other systems that exist in multiple sites of the supply chain system. The cryogenic supply chain in the UK was also used as a case study by the authors to demonstrate the viability of their deployment.

In Table 1, we have summed up part of the related works done to design, build, and realize a Digital Twin by using different architectures and the agent architecture as well.

In the context of using agents in modeling and simulation and integrating large-scale and complex systems with real-time requirements, some works have been carried out to investigate this matter. The work proposed in [19] selected multi-agent-based modeling and simulation (MABMS) technology over traditional methods to simulate a large-scale system like a high-speed train (HST). The approach enables the simulation of the relationships between the individual and different HST's components.

Anyhow, there are challenges which are encountered, specifically when deploying a system with a real-time requirement like IoT with agent-based modeling paradigm [20]. According to the authors of the [21], the absence of methods and mechanisms that can dynamically incorporate real-time input makes it impossible to use agent-based modeling for real-time simulation. Therefore, they tried to address this drawback in their work by showing how data assimilation techniques like the unscented Kalman filter (UKF) may be used to incorporate pseudo-real data into an agent-based model at run-time.

The claim about the drawback of current agent-based modeling approaches to incorporating real-time data to make precise decisions or forecasts the near future is also expressed in the paper [22]. Thus, the authors introduced an approach to increase the model-based predictions using agent-based modeling in real-time. The

Table 1 Comparison of the related work in the literature

Description	Approaches and tools	Domain	IoT/CPS support	Agent-based
Digital Twin based on web services and augmented reality [7]	Web services, augmented reality (AR)	Industry and manufacturing	Yes	No
Proof of concept of Digital Twin [8]	Web-based, finite element method (FEM) simulation, CAD	Industry and manufacturing	Yes	No
Digital Twin for a sheet metal punching machine [9]	3D modeling, CAD/CAM, Ethernet/IP	Industry and manufacturing	Yes	No
Digital Twin for cloud-based CPS [10]	Bayesian network	Automotive industry	Yes	No
Digital Twin for the micro-punching machine system [11]	Deep learning, computer numerical control	Industry and manufacturing	Yes	No
An architecture of Digital Twin in smart grid [12]	Prognostic and health management system	Smart grids	x	No
Digital Twin of a wheat plant [14]	Multi-agent approach	Agriculture	x	Yes
Digital Twins for smarter cities [15]	Multi-agent approach, MARS framework	Smart cities	x	Yes
Improve the robustness and resilience in the Digital Twin [16]	Agent-based architecture	Medical production	x	Yes
Digital Twin integration in multi-agent cyber-physical manufacturing systems [18]	Agent-based modeling, RFID	Cyber-physical manufacturing	Yes	Yes

method utilized agent-based modeling through combining parameter calibration and data assimilation (DA).

Despite all the aforementioned approaches that discussed building a Digital Twin with a variety of approaches, techniques, and methodologies, there is still a lack of methods capable of handling the complexities of CPS components and adapting to the unpredictable changes and uncertainties of the CPS systems. Thus, some researchers have embraced using more intelligent and smart methodologies such as agent-based and multi-agent systems, which offer the ability of an individual component to analyze and act autonomously and interact with other actors to solve mutual and more complex problems. Hence, implementing intelligent techniques that synthesize complex problems into smaller ones and have components that can take independent actions to solve every particular problem should be appropriately addressed. Therefore, in our study, we propose an intelligent approach for building a Digital Twin based on the agent paradigm by applying agent-based modeling and multi-agent systems techniques.

3 Background

This section gives a general overview of the key concepts and terms used and the technologies deployed in our proposed approach. Fundamental topics such as the intelligent agent concept, multi-agent systems programming paradigms, and agent-based modeling and simulation have been discussed. As an emergent technology, we discuss the different terms, concepts, and key components of Digital Twin that are proposed in the literature. Finally, in a related context, CPS is discussed, and some examples of its applications are given.

3.1 Intelligent Agents and Multi-agent System

Multi-agent systems are organized systems where they consist a group of agents (i.e., society) interacting and cooperating with each other to reach their goals that leads to solving a particular problem [23].

Nowadays, the evolution in computing has led to open a wide door for many problems to emerge, and they tend to be composite and more complex than before. Many of those problems are pretty hard to solve by a single agent, entity, or individual process. Thus, in the multi-agent architecture, complex issues could be dismantled into small and separate segments and then assigned them separately to respective agents to be solved.

The term "agent" usually refers to an individual entity or component composed of essential features, capabilities, and characteristics (e.g., autonomous, proactivity, reactivity, and interactivity) that constitute the internal and external behaviors of this agent [23]. These features govern the behavior and the attitude of agents while

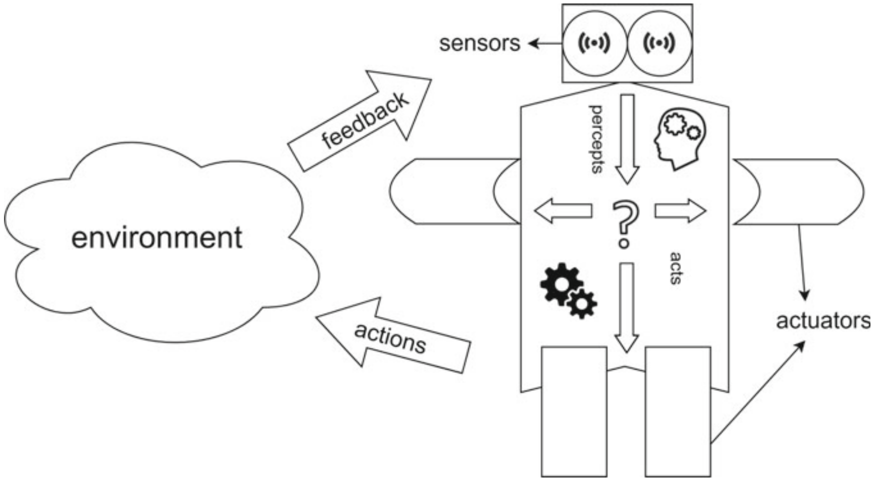

Fig. 1 Overview of the agent and its environment

interacting and communicating with the environment. The next figure (Fig. 1) gives an overview of how agents could be in an environment, and what are actions could happen in such systems.

The multi-agent paradigm has been applied by researchers in various disciplines to address distributed systems and environments that have high levels of complexity. Therefore, the benefit of using the multi-agent systems can be summarized into three major points; (1) single agent can focus and keep track of its own environment and its software-specific nature; (2) the interaction between different agents can be modeled and monitored; and (3) sub-components of the system can deal with the difficulties and complexities that encounter agents [24].

Decentralization is the main concept in MAS-based frameworks where the coordination and the other tasks (e.g., planning, execution sending information, etc.) for keeping the connection between agents are not controlled by one agent so it will not suffer from the overload caused by controlling such tasks [24]. Typically, in the MAS-based frameworks, there are requirements that must be adhered to when designing multi-agent systems such as the coordination among the agents as well as the protocols that the agents must follow when they interact with each other. Due to the limitation of the capabilities in some agents, normally, agents rely on other agents to provide some information or to provide some resources (e.g., high memory requirement or big-data processing, etc.). Following this mechanism makes agents in the multi-agent systems frameworks work cooperatively on a global plan.

Building evolving software is one of the significant challenges in systems existing these days, where the environment changes dynamically and rapidly. Hence, it is important to have software that can observe and then interact and respond to the changes and finally adapt itself accordingly [24]. Such systems are usually equipped with sophisticated software and algorithms that imitate intelligent behavior.

An intelligent agent is a type of agent that has an autonomous behavior and acts toward solving a certain problem (achieving a goal), by using its other components and entities such as sensors, to observe the environment and learn, then achieve their goals by commands or by providing information. A very well-known example of a programming model of intelligent agents is the belief-desire-intention (BDI) software model [25], where agents can have a set of beliefs that describe the environment and its features; a set of desires that are computational states that the agent should maintain; and finally, a set of intentions that any individual agent constantly works to achieve and which leads to solving a problem in the agent's environment [3].

3.2 Agent-Based Modeling and Simulation (ABMS)

The field of agent-based modeling and simulation is related to multi-agent systems and artificial intelligence [26]. Basically, it is a computational modeling approach for modeling and simulating complex systems consisting of multiple autonomous agents interacting with their peers as well as with the environment in which they operate. Agent-based modeling and simulation is common and well-known modeling approach to model social systems and decision-making processes [26]. Agent-based modeling and simulation is used to model and simulate the dynamic actions and processes in the system and also the communications between the agents in the environment.

Currently, agent-based modeling and simulation is a widely used model approach that is applied to simulate large-scale and complex phenomena. In agent-based modeling and simulation, an agent is the main entity in the system, where every agent represents an independent component in the system and eventually a set of agents construct the system. Every agent in agent-based modeling and simulation is an autonomous entity that has certain attributes, plans, goals and engages with other agents for facilitating and solving a common problem [3]. On the other side, M&S approaches use other approaches and implementation such as modeling languages for complex systems like metamodeling tools (EMF, Ecor, Xtext, and MOF) or such general-purpose modeling languages like SysML and Unified Modeling Language (UML) to model the components in the target systems [3].

Evaluation and forecasting are among the main objectives for the modeling and simulation frameworks as well as deriving insights to predict the performance and the behavior of the system which could be very crucial in certain systems. The complexity of autonomous agents consists of an emerging behavior of agents which can vary from the basic behavioral status like "if–then" to more complex cognitive and reactive attitude, also complexity in agents could be represented as an independent behavior of agents without an external direction that drives an agent when encountering a situation in the environment [3]. Modeling different agents with distinct objectives and behaviors usually are carried out using agent-based paradigms.

Another similar modeling paradigm to build agent-based systems is by using the individual-based model (IBM) that has the feature for individual decision-making during the simulation process [27]. Originally, the individual-based model was first proposed in a study in 1998 by Huston, DeAngelis, and Post [28]. This model was developed and especially deployed in ecology modeling. In ecology, there are many questions that were not addressed by existing standard approaches and models that were used at that time. Existing models were not able to address many questions and behaviors are related to ecological systems like (aging and mating, etc.). The existing systems treated all the individuals in the system as homogeneous, which resulted in not observing any individual behavior and the entire population acted similarly. Thus, this kind of individuality is really important to some environments, where individuals have their own actions that can affect the environment or be affected by the environment. Therefore, for designing an individual-based model, there are three primary factors to be considered, (1) agent behavior; (3) agent-agent interactions; and (3) agent-environment interaction. Individual-based model is intended to be used in complex adaptive systems where it has to deal with different emergent behavior and interactions between individual agents and with the environment [29].

Agent-based approaches enable software designers to design, prototype, and deploy a system unit (as agents) which have specialized and complicated capabilities and features that permit them to do several sophisticated processes like learning, reasoning, and acting toward the specified objectives in the domain [30].

Due to the complex world that we live in and the complexity of the systems that we need to analyze and model, the need for intelligent modeling approaches has increased drastically. Also, the need of designing software and systems which are capable of evolving over the time of operation according to the changes in the environment. Thus, the use of agent-based modeling and simulation methods over conventional and static modeling approaches could help us to address high complexity levels that exist in large and complex systems [31].

Various agent-based programming models are existing and have been used in several fields. Those models are used as the foundation of many agent-based programming languages. According to the surveys conducted in the [25], the beliefs, desires, and intentions (BDI) model is the most popular agent-based programming language model that is used to implement many agent-based systems. Among the other models that are used to build agent-based systems are rule-based, domain-specific language (DSL), and object-oriented (OOP) [25]. Also, it is reported that the Java programming language is one of the most used languages due to its cross-platform features provided through its Java virtual machine [3, 25].

3.3 Digital Twin and Key Concepts

We live in an era where robotics, cyber-physical systems (CPS), and the Internet of Things (IoT) have provided an outstanding foundation to build advanced industrial solutions by enabling the connection of the operations in the physical reality with the virtual computing infrastructures. With the wide range usage and utilization of CPS and IoT in the industrial and manufacturing systems, many challenges in the domain of cyber-physical systems and the Internet of Things have arisen. There are many examples, such as integration of cyber and physical parts, handling and processing real-time data, reporting, resource management, forecasting and safety verification, etc. Different approaches from the academic community as well as from industrial vendors have been proposed to tackle the different challenges in this domain. One of the most promising concepts to address different challenges of the CPS that were introduced in the last decades is the "Digital Twin".

Since introducing the concept of Digital Twin in this millennium, a considerable number of researchers and technology specialists have tried to give their perspectives and define a Digital Twin in different scopes of science and industry. Different terms and definitions were given. Up to the recent times, there is no consensus on an agreed and exact definition for the Digital Twin neither in the research community nor from the industrial providers who are building and using this technology [1].

However, the basic and the foundation of the Digital Twin concept was initially introduced by Dr. Grieves during his presentation called "Conceptual Ideal for PLM" at the University of Michigan [6]. Later, National Aeronautics and Space Administration (NASA) adopted the concept [6]. In NASA, Digital Twin is defined as "an approach to enable a suite of comprehensive multidisciplinary physics-based models that represent all of the physical materials, processes, and products, and ultimately incorporating these capabilities in the production and operation of spacecraft" [32].

The use of Digital Twin is different from one implementation to another. For example, if the Digital Twin is used during the design phase, then mostly the purpose of using it is verification and validation. On the other hand, if it is used as a simulation model to simulate the behavior and properties of the real physical system, then the purposes such as testing or collecting real-time data. Fundamentally, a Digital Twin can be tailored based on the requirements and field of usage.

Many Digital Twin implementations have been proposed by different vendors in the industry from commercial frameworks like Azure Digital Twins, General Electric Digital Twin, etc., or from open-source communities like Eclipse Ditto (https://www.eclipse.org/ditto/) or Eclipse Vorto (https://www.eclipse.org/vorto/).

Before realizing a DT, first, we should understand what the DT is exactly and what is the purpose behind a building and using such technology. However, despite the fact there is no single use of the DT, there is a general perspective for what are the objectives and the benefits of building a DT which most of them are analysis-oriented objectives, such as visualization, testing, fault-tolerance, error detection, and self-correction.

Moreover, it is noteworthy that there are many terms used in the circle that outlines a Digital Twin technology, such as a digital shadow, digital thread, digital model, physical asset, digital asset, and twinning. These terms usually create confusion and misunderstanding, so they should be clearly defined and distinguished from each other. For instance, in the DT design, there are three main design variants (digital model, digital shadow, and Digital Twin) which are pointed out in the [33]. In those design variants, every variant has a digital object (DO) and physical object (PO) entities which are other terms used to describe digital asset and physical asset, respectively. In other meaning, DO represents the digital copy of the system under

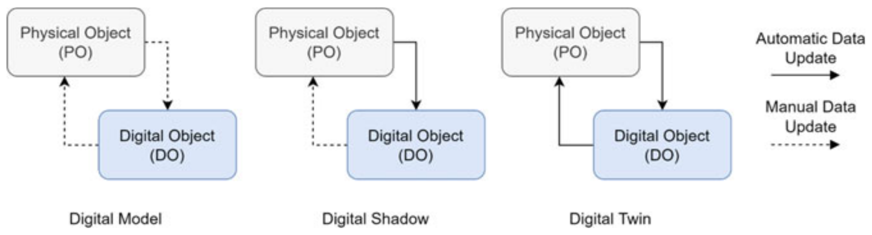

Fig. 2 Design variants of physical and digital objects

study which could be realized as a simulator, while the PO represents the physical understudy in the real world. The three design variants are different in the type of connection and the data flow between the physical object and the digital object, and this can be seen clearly in Fig. 2, where the two types of connections are defined as a continuous and dotted line.

For instance, the digital model has a manual data connection between the digital object and the physical object, and this connection is manually updated and controlled. Consequently, any change in the status of the physical object will not affect the digital representation (digital object) and vice versa. In the case of digital shadow, there is a partially-manual connection and a partially-automatic connection between the physical object and the digital object, which means changes and updates in the physical object lead to updating the digital object, while the opposite direction is manually maintained. On the other hand, we can describe the connections and the data flow that exists in the Digital Twin as a fully synchronized bi-directional connection, and this means that any change in the physical object will be propagated to the digital object; and usually, the connection from the digital object to the physical object is for controlling and orchestrating the physical object [33].

Digital thread is another concept that is related to Digital Twin. Digital thread is a connection link with main stages representing the product's life cycle from the beginning to the end life of the product. The thread is a data-driven link that includes phases from the concept and design to the operation and post-life of a product, and it is envisioned to be the essential source of data and information of a product instance in a short-term or a long-term life. Digital thread can be viewed as the essential source of information to update and feed the Digital Twin. It could be a very valuable source of information to build the next generation of the product by analyzing and synthesizing the available data and information of the existing product. Also, such type of information could lead to use more efficient strategies to operate the next generation. Many improvements and better decisions could be taken based on data-driven digital thread [34]. The next (Fig. 3) highlights the main concepts such as Digital Twin, digital shadow, and the digital thread engineering process as well. Also, it shows the physical asset as a physical system: an airplane which can be connected to either a Digital Twin or digital shadow according to the data connection model.

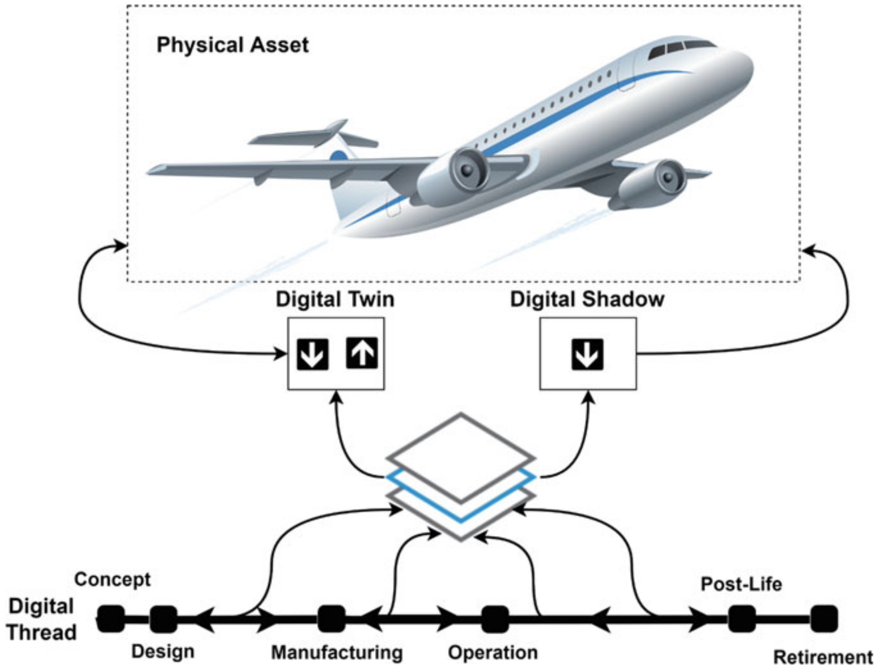

Fig. 3 Overview of the different concepts: Digital Twin, digital shadow, and digital thread

3.4 Cyber-Physical Systems

Cyber-physical systems (CPS) are powerful and promising systems that consist of multiple physical parts which are engineered, operated, monitored, and controlled by cyber elements (i.e., embedded systems) that are fully integrated and intertwined with physical parts. The process of coupling and mapping between the cyber world and the physical world offers enormous capabilities and an expanded range of CPS applications. Building CPS is achieved by the confluence, diffusion, and merging of different technologies and concepts. For instance, CPS should ensure real-time data flow from embedded systems with several microcontrollers, sensors, and actuators, and this could be achieved only with tight integration and coupling of the physical and cyber parts.

Leveraging such technology makes it possible to achieve considerable social benefit and economic impact. Besides that, the cross-disciplinary nature and the flexibility of the CPS systems gives an advantage and qualifies them to be implemented and utilized in a wide range of fields and areas such as health care and medical devices, transportation, agriculture, manufacturing, aerospace, transportation, and robotics [35].

4 The Proposed Architecture

Several Digital Twin architectures especially those associated with the Industry 4.0 domain are proposed in the literature, and they vary from one to another and include different development implementations, approaches, and techniques. In the next lines, we try to summarize some of followed development approaches and the architectures that have been utilized to realize a Digital Twin.

Digital Twin architecture based on big data is one of the approaches that has been followed by some researchers to implement the Digital Twin [36]. The architecture based on big data has advantages that big data can bring to the Digital Twin, such as the variability of the data which concerns dealing with real-time data as well as the capability to deal with historical data. Also, big data can bring other features such as advanced data processing methods, data mining, data analysis, and cleaning which can improve the product life cycle.

Another architecture is Digital Twin based on virtual reality (VR) and augmented reality (AR) which can propose essential features in some domains [37]. Fundamentally, VR and AR technologies are based on the concept of linking physical reality to virtual reality through simulation. So, VR and AR are utilized to build Digital Twin for purposes such as training, maintenance, prediction, analysis and forecasting.

The deployment of Digital Twin, based on the Internet of Things (IoT) concepts and methods, is well accepted in the industry due to the advanced technologies, such as reliable data exchange and efficient communication provided by IoT.

Another approach is based on cloud computing. Nowadays, cloud services are not just limited to storage services, instead, they provide a wide range of services that almost include everything needed for software and system development. Many big companies offer their services for building Digital Twin based by combining the cloud computing features with the IoT capabilities. For example, Microsoft provides through their cloud computing service (Azure), as a service to build a DT through their platform (Azure Digital Twin), Amazon offers a tool called (Amazon Sumerian) through their cloud service (AWS IoT). Also, among the companies that provide services to realize a Digital Twin is Oracle, through their cloud service (Oracle Internet of Things Cloud Service).

Digital Twin architecture based on modeling and simulation (M&S) which was an early architecture that was used to build the Digital Twin. NASA was working on this topic where high-fidelity simulation integrated with the vehicles to manage the vehicle's health and observe the maintenance history, and this mirroring process will provide a good level of safety as well as a reliable product [38].

Currently, many vendors provide modeling and simulation tools that can be very handy to realize a Digital Twin. Many software engineering paradigms are available, and they have been used for years to build complex systems. Model-based engineering (MBE) is an excellent example of a paradigm that could minimize the complexity of various systems. Therefore, architecture such as MBE and other tools, languages, and techniques were used and considered to build a Digital Twin. Architectures based on artificial intelligence (AI) approaches were also introduced in the literature, and machine learning and deep learning algorithms and methods have been discussed and deployed to implement Digital Twins [39].

Although different approaches and architectures to build a Digital Twin have been presented and discussed by various researchers, still, approaches and architectures that have utilized agent paradigm are still rare and relatively new; also, several aspects in the agent paradigm still need to be discovered and explored. Therefore, this section is dedicated to discussing the proposed architecture and explaining the main components to construct a Digital Twin based on agents technology. Several tools, frameworks, and methods are used and integrated to compose the final Digital Twin. We will try to tackle every technology separately and demonstrate how different components are incorporated into our architecture.

4.1 General Overview

As stated in various definitions, the main characteristic of the Digital Twin is to have a physical asset and its virtual counterpart with a connection that transmits the data flow bi-directionally. The Digital Twin under operation is usually used for different inspecting and monitoring tasks (testing, verifying, debugging, etc.) of the physical elements by leveraging the features that are provided by the twinning of the physical world into the Digital Twin.

In the context of IoT and CPS, different physical parts are aggregated and then linked and connected to a cyber-part to comprise the whole system. In such systems, every physical component has its own capabilities and sub-processes (intelligence, optimization, computation capabilities, algorithms, error detection techniques, etc.).

In Digital Twin architecture, abstract representations of physical parts are modeled and then twinned and combined as a virtual representation. All those (i.e., physical and digital) components are aggregated together to create a Digital Twin. Representing physical world as virtual and digital entities requires using modeling and simulation tools. However, the heterogeneity of the components in the CPS/IoT systems imposes switching and choosing adequate modeling and simulation methods. In addition, to build a Digital Twin, specific requirements such as synchronization and real-time data flow with the physical asset should be constructed in order to have an accurate simulation for the physical asset in the Digital Twin.

In our implementation, the aforementioned characteristics are realized by raising the level of intelligence by adding an intelligent layer to represent the components of the system, all that was achieved by utilizing the intelligent agent architecture and multi-agent systems. Therefore, in this context, multi-agent systems architecture has been applied to implement and develop a Digital Twin. In the architecture of multi-agent systems, multiple agents that represent different components of the system cooperate, coordinate, and interact with each other to tackle a mutual problem. In addition, the capabilities of agents such as autonomy and interactivity behaviors play a significant role and provide immense support in resolving complex and interrelated concerns [5]. Autonomous behavior in agents can result and take shape as different actions like analyzing, negotiating, coordination, cooperation, and acting proactively without being dependent on external intervention in order to achieve the objectives that are designed for their agents [5].

As a result, Digital Twin for CPS/IoT could be built by taking the advantage of the features that are provided by the multi-agent systems and the intelligent agent paradigm. Before diving into the details, we would like to give our conceptualization of the metamodel [40] that has been adopted as the foundation of our proposed architecture. The metamodel is elaborated to depict at a high level how the Digital Twin system is developed and deployed based on the agent-driven architecture.

The metamodel provided in (Fig. 4) describes how a Digital Twin is, in fact, a system that operates and targets a specific domain. The domain is targeted by a system, which is basically a Digital Twin. The targeted domain reflects the system environment and is the main source of the requirements, and thus the implementation of the Digital Twin will be adjusted as the domain is changed or switched, and finally, the evaluation is performed against the collected or modified requirements. Theoretically, many parts of the system can operate without any change if the domain has changed, but still, we have to consider every domain's specific requirements. It has been mentioned and discussed before in Sect. 3.4 that the Digital Twin has multiple design variants which depend on the data flow and the level of the integration between the physical and the digital objects. This point is highlighted in the metamodel where Digital Twin system can be either a Digital Twin (DT) or a digital shadow (DS) based on the data connection in the final implementation where if the connection is bi-directional, then the system is a Digital Twin and if the data connection has a unidirectional flow, then the system is a digital shadow. It is clearly described in Fig. 4 that the Digital Twin architecture is designed and deployed based on intelligent agents as in our implementation. In addition, this architecture uses a Digital Twin model that is deployed inside the Digital Twin that contains the information of the integration, implementation, and the deployment of the physical and the digital assets.

4.2 Main Components of the Architecture

This section gives the big picture of the suggested architecture where the main components are presented and explained. In Fig. 5, a general overview of the agent-based Digital Twin architecture is given.

4.2.1 Agent-Based CPS/IoT

The main goal of using the proposed approach is to build a Digital Twin for a CPS or IoT system. As illustrated in Fig. 5 specifically in the "agent-based CPS/IoT" box, CPS or IoT system is constructed and connected to the environment by the sensors that sense and take the measurements from conditions in the environment, as well actuators that control the environment by taking actions that are sent in commands

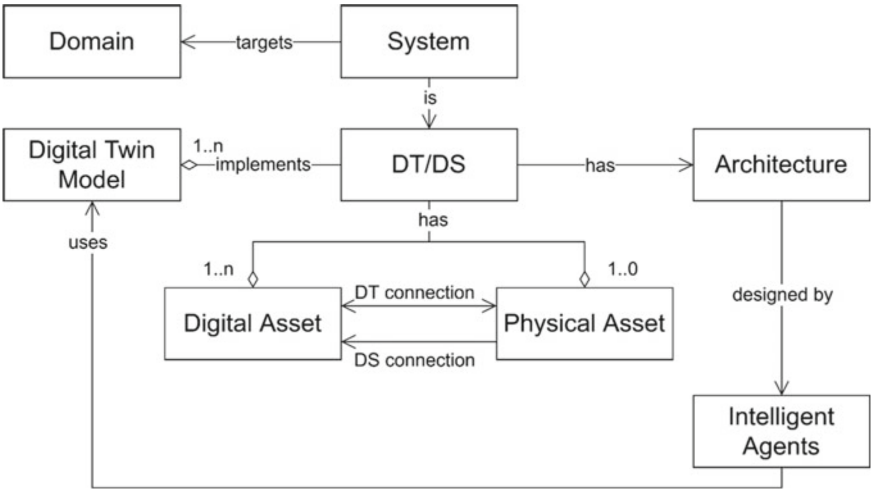

Fig. 4 Digital Twin system metamodel

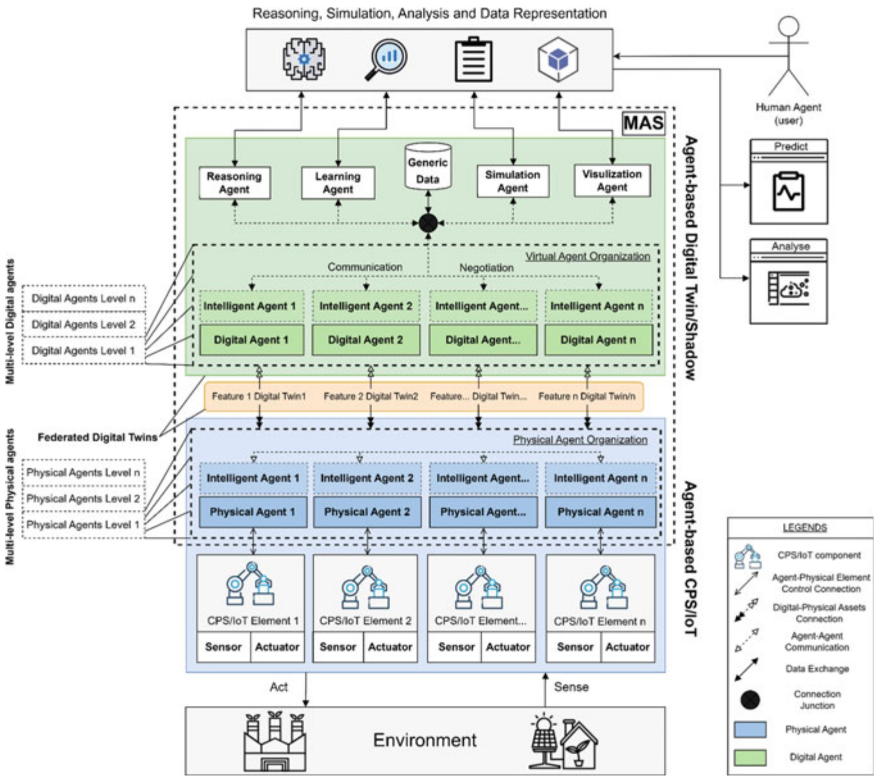

Fig. 5 Architecture for intelligent agent-based modelling for Digital Twins

from the CPS, actions are taken based on the feedback sent after processing the sensed measurements taken beforehand.

In our proposed architecture, the CPS or the IoT system is built, programmed, and controlled by an agent-based platform. Thus, the CPS/IoT has the features of agents that provide the system with decent levels of intelligence. Despite the fact, the level of intelligence varies from one implementation of agent-based architecture to another, as well as what is the model used for programming. In the previous figure shown in Fig. 5, the agent-based CPS/IoT system comprises sensors and actuators that are connected directly to the system, and at the top, there is a software agent layer that controls the entire CPS/IoT system. Different CPS/IoT systems could be included in the agent-based architecture, but every individual system should be part of the same agent organization.

4.2.2 Agent-Based Digital Twin

The agent paradigm is the essence of the proposed architecture. As illustrated in Fig. 5, the "agent-based Digital Twin/digital shadow" green box comprises digital agents of the Digital Twin's virtual assets (located in virtual agent organization) and the other main agents are also defined, initiated, and located there. This box contains the Digital Twin major agents, which can be listed as reasoning agent, simulation agent, learning agent, and also visualization agent, and lastly, the generic data, which is basically a data repository of the Digital Twin, and it's also could be represented as an agent as well.

For a brief description, reasoning agent is responsible for the reasoning process (i.e., reason about the situation and takes decisions according to the context and finally chooses the best available plan from agent's set of plan) and establishing the connection and the communication with the virtual agent organization. The virtual agent organization consists of abstract digital agents which may communicate with each other and other agents as well. Every digital agent is designed as an intelligent agent that takes the responsibility to negotiate with other agents to achieve its set of goals.

The simulation agent is in charge of the coordination and setting up the simulation properties and the environment based on the implemented modeling and simulation approach. The simulation agent sometimes depends on an external agents or inputs from other simulation processes which may be triggered by running and executing the simulation agent. The simulation agent can communicate, interact, cooperate, or negotiate with other agents to perform various specific tasks like reporting, simulation, and prediction.

The other major agent is the learning agent. In fact, this agent mainly communicates with the data repository of the Digital Twin and can have specific access to any data type, such as historical data (known as digital traces), where this agent can apply machine learning or deep learning algorithms to this data to learn from the Digital Twin system history and provide visions and insights of possible future scenarios. In addition, by using the learning agent that analyses the digital traces, administrators, and Digital Twin users can observe the performance and the behavior of the physical components and make improvements if some parts perform poorly and replace them with better versions.

Visualization agent is responsible for presenting data as a form of useful information that can be utilized to improve, maintain, and operate the physical components safely and efficiently.

Basically, human agent represents the administrator of the system, and he has the permission to perform all these tasks if required. The last component in this main box is the generic data or data repository that is responsible for storing and collecting data from every agent in the physical agent organization, digital agent organization, and the entire MAS system. The collected data can be divided into several categories and forms (e.g., historical data, maintenance data and real-time operational data, etc.).

4.2.3 Simulation and Analysis

In general, the purpose of designing and building a Digital Twin is to simulate physical components and get information and the real-time updates of the system's status, above that, a Digital Twin could be very useful in designing, forecasting, or evaluating the physical systems. Thus, as shown in the previous figure (Fig. 5), the main goal of building a Digital Twin is to generate reports and perform analysis tasks or predict the scenarios for some conditions or situations.

The reports and information gathered from the Digital Twin could be sent to human agents responsible for such a system so they can analyze those reports accordingly. Also, these reports might be sent to other software agents where they decide, act, and make a decision based on this information.

The simulation agent in the architecture is responsible for performing simulations on the DT. This agent is programmed or implemented using modeling and simulation tools, and it may provide a graphical simulation and visualization (2D or 3D) to represent and view the simulated scenario from the real one. Indeed, implementing such an advanced simulation for the DT requires using powerful tools and technologies, but such a system could be very easy to comprehend and used by users.

Deploying an agent-based modeling environment depends on many factors and requirements that should be considered during the modeling of the environment. There are several languages and frameworks that have powerful capabilities when it comes to deploying an agent-based modeling and building an agent-based simulator. Some of those languages are NetLogo, MASON, Repast, GAMA, SARL, and AnyLogic. An early phase in this work will be the process of selecting the proper agent-based modeling language that suits the needs of this project which is mainly building a DT. Then, the constructed modeling environment will be initiated by the simulation agent that will be connected with CPS/IoT components through the physical agent organization. Thus, the simulation agent will use the real-time data generated from the CPS/IoT components through the physical agents or historical data stored in a data repository (database). Then, this data will be used to simulate a particular situation and observe the behavior of the current system. As in

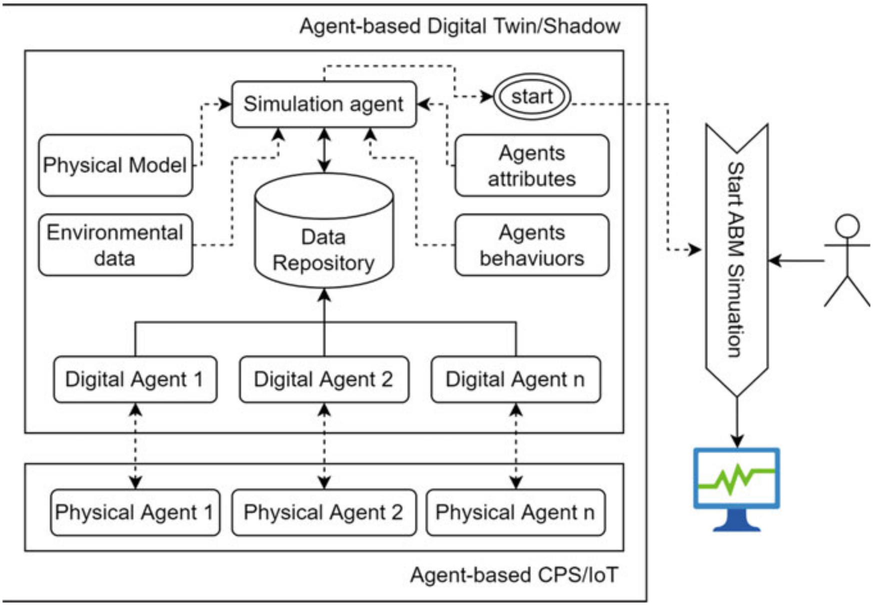

Fig. 6 Simulation agent in Digital Twin

Fig. 6, the simulation agent is an intelligent agent which initiates and coordinates the agent-based simulator in the Digital Twin.

4.2.4 Learning and Reasoning

Logical behavior is something complicated in human brains, and this behavior comes from years of observing, reasoning, learning, and adapting to any encountered situation. In computers, the issue of applying such behavior in software is really complex and requires the adoption of intelligent algorithms, methods, and techniques to reach a similar level of this behavior. In the agents' paradigm, the reasoning mechanism is one of the key elements to achieving intelligence in agents. Thus, some architectures and approaches have been proposed to solve this issue. For instance, logic-based (symbolic) is one of the architectures that take advantage of representing the human knowledge symbolically and which makes the encoding and understanding by humans easier [41]. Also, a model named belief-desire-intention (BDI) has a deliberative architecture of BDI that relies on the reasoning about the actions that its agents take [41].

Learning is the field of applying machine learning techniques, methods, and algorithms in applications for problem-solving. Learning in agents is the same, except the application space involves agents that compose the system under inspection. In machine learning, three main approaches are mainly applied to different problems.

The learning approaches are supervised, unsupervised, and reward-based learning. The main difference between these methods is the type of feedback provided to the learner by the critic [42]. Learning and reasoning agents can provide the Digital Twin with powerful capabilities to address complex and complicated challenges.

4.2.5 Multi-level Agents for Local Balancing and Self-adaptation

In some complex systems, there is a need to perform some heavy and extreme processing computations. The load on a specific part of the system or software can lead to some issues that affect the whole system performance like delays, freezing, and no responsiveness in the system. Thus, it is always mandatory to consider such requirements in the design phase of the system in order to avoid unpredictable behaviors and failures.

There are solutions to such issues like using a balancing strategy, where if intensive processing tasks are required, the system can distribute this task to different parts of the system and then aggregate the results. Load balancing is quite essential, especially in systems with limited resources like many physical components. Sometimes, a trade-off should be considered when using balancing, specifically, if the system is time-sensitive, for example, if the physical component gathers the data and then sends this data to be processed in the cloud. In this situation, delays are expected due to the time required to send data, process it, and finally, send the feedback rather than just process the data directly in the physical component itself.

Nevertheless, in our architecture of the agent-based Digital Twin, we have considered this requirement. The solution for such issues is to make agents self-adaptive and have multi-level physical agents in the physical asset and multi-level digital agents in the digital asset. This means agents will be designed to assess the tasks assigned to them and then decide whether it is required to balance the load with other agents, or they can continue and process and execute all the tasks by themselves. This concept is illustrated in the main figure (Fig. 5) of the proposed architecture.

4.2.6 Federated Digital Twins

Even though individual Digital Twin that targets a specific CPS or IoT system could be quite complex, the complexity level can still increase if we considered to have more than one Digital Twin and merging them under an extensive and inclusive system.

To give a clear and concrete example, in a realistic scenario, suppose we have a factory with many production lines and robots; every specific CPS has a particular role in the production and manufacturing process. Also, suppose that we have Digital Twin for every specific CPS system in the whole factory; the number of Digital Twins could be pretty high, but the major issue is not in having multiple Digital Twins; it is specifically how we orchestrate, manage, and communicate between these Digital Twins to address a specific issue in the entire system. For instance, ensuring safety in a factory could be one of the mutual issues that concern all the parties in the system (i.e., all Digital Twins and their CPS). It is also possible to have multiple Digital Twins in from a single CPS system if we have considered every feature of our interest in this physical system as a Digital Twin with its functionality.

Therefore, to achieve such a requirement, we suggest having a higher-level organization called "Federated Digital Twins", in which we integrate, organize, manage, and supervise all sub-Digital Twins of the entire system. In such a scenario, standard communication protocols that are used in agent-based and multi-agent systems like FIPA communication language can simplify and facilitate the integration of multiple heterogeneous agent-based Digital Twins. Following this context, we intend to investigate and explore how to achieve such a hierarchy for Digital Twins based on agent-based and multi-agent systems in the future works and investigations.

In the figure (Fig. 5) of the main architecture, we have elaborated a conceptualization of the "Federated Digital Twins" concept on a high level of abstraction. Different features of interest of the target CPS system are represented as individual Digital Twins and organized under the umbrella of the Federated Digital Twins of that system.

5 Reference Implementation

In this section, we try to give a concrete idea of the technologies that could be used for implementing the proposed intelligent agent-based DT architecture by taking into consideration the specifications of the domain and the tools and frameworks used in the deployment process.

The figure given in Fig. 7 outlines the life cycle and stages according to the International Standard ISO/IEC/IEEE 15288 [43] for the system life cycle processes that are followed to build a DT/DS with the consideration of implementing both the physical and digital assets. Thus, in the first two subsections, we talk about physical asset and how to build its related system and sub-components, and then we discuss about the digital asset, and how it could be developed and integrated with the physical asset.

The rest of this section is made up of three subsections; agent-based CPS, agent-based modeling and simulation, and agent-based Digital Twin. In addition, we introduce a table that lists agent-based languages and frameworks for CPS used to build and realize different systems and solutions for CPS. Agent-based modeling and simulations tools are listed as well in another table. The two tables are provided based on the information collected from websites and papers that present these frameworks, tools, and languages.

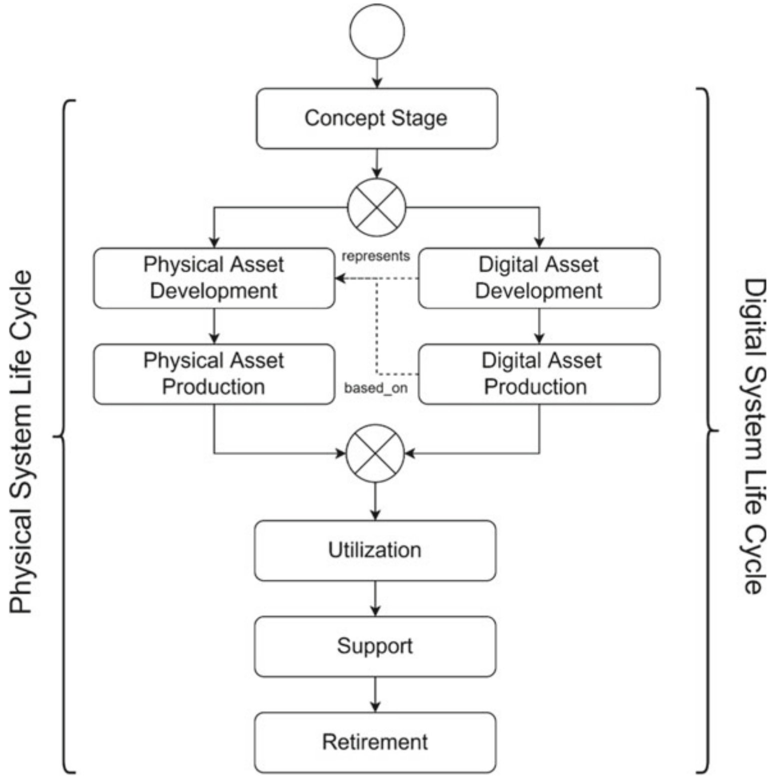

Fig. 7 Digital Twin system life cycle according to ISO/IEC/IEEE 15288 [43]

5.1 Physical Asset

As shown in Fig. 7, at the very beginning, it is mandatory to target a specific domain and scope in which the DT will be implemented, and at this stage is where the concept and design phases of the system are conceptualized. In the concept stage, the physical system representing the physical asset in the Digital Twin could be a new target system planned to be built, or it can be an already existing system that needs a Digital Twin to integrate with in order to leverage the features of DT on this CPS system. In both cases, we should identify the target parts of the system to be twinned and mirrored in the DT.

The implementation of the physical asset in the CPS/IoT systems requires collecting the parts and components. First, we should define our bill of materials (BOM) that lists all the main physical parts and components. We have to identify the products such as sensors and actuators and consider the compatibility between the hardware and embedded software (e.g., APIs and libraries). The quality of the products could have a big impact positively or negatively on the final system. Thus, choosing the proper technologies and products could enhance our system significantly. After that, we can start assembling the parts and construct the initial prototype and finish the "physical asset development" stage. Finally, we start the deployment of the assembled system. Generally, physical asset demand installing and using special software or specific programming language that are capable of running the embedded components such as sensors or actuators. After we finish this phase, we are having the final prototype of the physical system and we finished the "physical asset production" stage as described in Fig. 7.

5.2 Digital Asset

In the design phase of the digital asset or as it is sometimes referred to as (digital object, digital world, or digital space) predefined requirements must be identified in the "concept" stage with taking the consideration the implemented and the existing physical system (physical asset). Then, we have to identify physical objects and which components to be encompassed in the intended Digital Twin, For instance, if we have an IoT or CPS system that contains several sensors like temperature, pressure, CO2 sensor, humidity, etc., and our target is just to build a Digital Twin for the temperature sensor and the system that just retrieves the temperature readings, then we should write and define these details in the requirements in the concept stage. After that, we can design and model our specific system and start the development process, which can be realized by using programming languages and other tools and technologies. In this stage, it is crucial to build the system based on the properties of the physical asset, which means we have to consider the physical components' characteristics. The digital asset' behavior depends totally on the level of details of the physical asset required to be embodied in the Digital Twin. When the "digital asset development" stage is completed, a new stage named "digital asset production" will be started, where both physical assets and digital assets should be connected, coupled, and synced.

After this stage, we start the "utilization" phase where we utilize and start using both systems as a single working unit. According to the fundamental definition of Digital Twin and digital shadow, if the working system provides unidirectional data flow from the physical asset to the digital asset and the data are just sent from physical components like sensors, then we have a digital shadow, and in this case, the system could be utilized for just limited tasks like monitoring, simulation, and inspecting purposes. On the other hand, if the system can establish a back door channel (bi-directional flow) from the digital asset to the physical asset besides a connection from the physical asset to the digital asset, then we have a Digital Twin. In such a case, the system could read from physical components like sensors and issue and send commands and feedbacks to the actuators to influence the environment according to the fetched data from the sensors and this similar to a feedback control loop.

In the "support" stage, several calibration iterations are required to guarantee and make sure physical asset and their counterparts are error-free and work properly and adhere to the requirements designed in the concept stage.

5.3 Agent-Based CPS

This subsection discusses and lists the most and widespread tools that are available to implement a CPS using the intelligent agent concept. According to the surveys [25, 44] that are conducted to compare and list the available tools in this domain, we will discuss the most relevant tools that are suitable to tackle such systems. Table 2, gives an overview about the tools and frameworks are discussed in this subsection.

SARL (http://www.sarl.io/) is the first language in our list is which is proposed by the authors in [45]. The language is basically used to build systems based on multi-agent systems. It deals with many features such as autonomy, dynamicity, interactions, decentralization, distribution, and reactivity. If SARL language is able to provide such features to build systems based on MAS, then it will be capable of implementing complex and distributed systems by providing such a language. Developers of SARL used Xtext and Xbas to build the language with inherited features. For developing multi-agent systems, SARL defines keywords that are specific for the multi-agent system, also it defines components that are reusable and can describe the behavior and the concepts of the agent [44]. Despite the options to use SARL with other sets of tools and frameworks, it can be used with a set of tools, platforms, or frameworks to support its execution, such as the Janus platform or the TinyMAS platform. It is unfortunate that SARL cannot specify the deployment of the multi-agent systems because it does not have support for programming tools. Thus, Janus is the main official open-source Java 1.8 run-time environment that provides many features for developers to deploy, create, and monitor multi-agent applications [44].

Table 2 Agent-based programming languages and frameworks

Name	Approach (Model)	Language	CPS support	Last update	Source code
SARL	DSL	Java	Yes	2021	Open source
Jason	BDI agents	Java	Yes	2021	Open source
Jade	FIPA	Java	Yes	2017	Open source
JaCaMo	BDI, organization, and environment	Java		2020	Open source
SPADE	BDI agents, XMPP	Python	Yes	2021	Open source
Jadex	BDI agents, OOP	Java		2021	Open source
LightJason	BDI agents	Java		2021	Open source
JACK	BDI agents	Java		2015	x

Jason (http://jason.sourceforge.net/wp/) is another language for programming agents which is based on an AgentSpeak (L) and AgentSpeak enables agents with a set of plans which work according to different situations to achieve their goals. Basically, Jason is a Java-based framework that is extended from the AgentSpeak and which allows developers to build complex multi-agent systems. The features that Jason provides such as its extensibility allows users to customize the agent architecture and build software and multi-agent systems that can simulate real-world complex scenarios. Jason is a versatile language and gives its users the capability to model and include a major number of agents in the system, but one of the advantages of the language is that it is not intuitive enough compared to other programming languages, thus it can impose some challenges during the implementation of multi-agent systems using Jason [44].

JADE (https://jade.tilab.com/) is also another language for programming agents to build multi-agent systems. Jade is a widely used and popular language among multi-agent systems developers. Jade provides a set of features and a collection of tools that support and simplify the deployment and debugging processes. Jade platforms comply with the FIPA specifications and implement agents and every individual agent is composed of a set of behaviors. Jade offers dynamicity to add agents into the environment of multi-agent systems. Also, the JADE platform provides a wide variety of tools such as graphical tools for managing agents, as well as monitor and displaying the exchanged messages during agents' run-time [44].

JaCaMo (http://jacamo.sourceforge.net/) is a platform that is based on three languages and technologies that represent the different abstraction levels, Jason, CArtAgO, and Moise. Every technology is used to tackle a specific part of the system. Jason is used for programming agents and CArtAgO for setup and programs the environment and finally, Moise is used for organizing the multi-agent systems.

SPADE (https://spade-mas.readthedocs.io/) is a multi-agent language that is written in Python and provides features to have agents that communicate and talk with other agents and humans based on instant messaging (XMPP). So, it supports building systems that provide notification capabilities to know the current state of the agents in real time.

LightJason (https://lightjason.org/) is a language that is inspired by two technologies AgentSpeak and Jason, but developers designed it from scratch. The language is suitable for distributed and concurrent computing environments. The languages enable designing and building agents systems based on an extended language of AgentSpeak with new features like (lambda-expression, multi-plan rule definition, explicit repair actions, multi-variable assignments, and parallel execution and thread-safe variables) and the new language called AgentSpeak (L++).

Jadex (https://www.activecomponents.org/) is an agent-based framework that extends the service component architecture (SCA) approach with agent-oriented concepts and offers the capability to program distributed and concurrent systems where the system can be composed of many components that provide services to consumers.

JACK framework (http://www.agent-software.com.au/products/jack/) is the only proprietary framework in the table. JACK is a Java-based multi-agent modeling framework that supports the BDI model for building distributed and agent systems. Also, the framework provides GUI tools.

5.4 Agent-Based Modeling and Simulation

Modeling and simulation the behavior of agents mainly depends on the agent architecture and the approach used to build the agent system. M&S is widely used to have deep insights and understandings about different phenomena. In addition, building an ABMS simulation for a system that can imitate the exact behavior of the system agents in their real environment where rapid and big changes repeatedly occur before actually implementing it could be very crucial to build and construct a reliable and accurate system. According to the recently conducted reviews on the agent-based modeling and simulation tools and programming languages [25], there are numerous tools and languages that are focused on building simulation system by using the agent-based modeling and simulation approach. The most relevant and widely used agent-based modeling and simulation frameworks are listed in this subsection. Only updated and maintained frameworks from their developers and vendors are considered.

AnyLogic (https://www.anylogic.com/) is an industrial modeling and simulation tool that is used by many companies for various disciplines in manufacturing, transportation, rail logistics, ports and supply chains, etc. The framework supports modeling dynamic systems with an agent-based approach.

NetLogo (https://ccl.northwestern.edu/netlogo/) is the second framework in our list, which is very well-known and used in a wide range of universities to educate students about simulation and dynamic systems; also, the tool is used by researchers for building complex and distributed systems. NetLogo is a modeling framework for modeling agent-based systems, and it was evolved and developed for more than 20 years when the first version was released.

GAMA platform (https://gama-platform.github.io/) also is a powerful modeling and simulation tool that offers 3D capabilities as well as it fully provides geographic information system (GIS) features. The platform is based on an agent-based modeling approach; thus, it offers to build complex and spatial systems. The framework is built with its own language called GAma Modeling Language (GAML) which is inspired by Java and Smalltalk. The GAMA framework provides a clean and friendly user interface that enables developers to easily deal with their modes.

MASON (https://cs.gmu.edu/~eclab/projects/mason/) is a discrete event multi-agent framework that was built purely with Java as a core language. MASON offers many functionalities, from supporting and visualizing 2D and 3D to generating snapshots and movies as well as charts and graphs. The next table (Table 3) gives an overview and information about the available tools and the languages that are built on, source code, and some features like geographic information system (GIS) and 3D.

Repast (https://repast.github.io/) is a suite of cutting-edge, open-source, and free agent-based modeling and simulation tools. The family consists (1) Repast Simphony

Table 3 Agent-based modeling and simulation frameworks

Name	Language	3D support	GIS capabilities	Last update	Source code
AnyLogic	Java	Yes	Yes	2020	x
NetLogo	NetLogo	Yes	Yes	2021	Open source
GAMA	GAma Modeling Language (GAML)	Yes	Yes	2021	Open source
MASON	Java	Yes	Yes	2019	Open source
Repast	Python, Java, C++	Yes	Yes	2022	Open source

is a Java-based modeling toolkit that is easy to use and optimized for usage on workstations and small computing clusters, (2) Repast for High Performance Computing is compact, expert-focused distributed agent-based modeling toolkit built on the C++ programming language and intended for usage on supercomputers and huge computing clusters, (3) Repast for Python is the newest toolkit in the Repast Suite for agent-based modeling. It is built on Python, and it aims to make using ABM techniques for modeling large-scale distributed systems easier for researchers from diverse scientific communities.

5.5 Agent-Based Digital Twin

Digital Twin implementation differs from one approach to another in terms of the languages and frameworks that are used to realize it. Nevertheless, most approaches have standard requirements, firstly, the capability to program CPS and represent them as virtual elements; secondly, the instantaneous synchronization for the data flow between the physical asset and their digital counterparts. Thus, the first criteria to use an agent-based programming language for building a Digital Twin is to consider the capability to program and represent the physical components as virtual components, and also the capability to establish the connection between physical asset or the software agents that control them in order to acquire the data in real time and pass this data to their digital representatives. Table 2 provides and enumerates some of the agent-based languages and the frameworks that could be deployed and used to program and control a CPS. Accordingly, several of the languages and frameworks could be deployed to build an agent-based Digital Twin. In Table 3, agent-based modeling and simulation frameworks are listed. Agent-based M&S tools are used to build simulations to simulate real systems and scenarios based on agents, and thus, we may have a Digital Twin simulation. For instance, we could build a simulator that considers all the physical asset' properties included in the real and operational Digital Twin for conducting and performing more complex and extreme scenarios. Frameworks and tools that support the deployment of the intelligent agent-based models for simulation, such as a BDI model, are the GAMA platform, NetLogo, and MASON. The challenge in using agent-based modeling and simulation frameworks is the capability to connect the built simulator with the outside world, i.e., the ability to communicate with the system of the physical asset and receive real data. As a solution, a simulation agent responsible for conducting such simulations in the Digital Twin could be programmed and included in the Digital Twin. On the other hand, in general, selecting a proper agent-based language depends on the features provided by the language and its framework and for how far it is reliable and stable to deal with more complex and complicated systems. Thus, this decision could be taken based on concrete experiments and trials of the different tools and frameworks.

6 Case Study: Smart Inter Factory Logistics

This section is devoted to showing a proof of concept of an agent-based Digital Twin by introducing a smart inter factory logistics case study [46] and gives a full insight of a real scenario and how the mentioned points above about building and implementing a Digital Twin for the real system are considered. Therefore, we introduce a concrete case study that focuses on the implementation of an intelligent agent-based Digital Twin for smart factories and discusses the implementation details and the deployment specifications. Also, this proposed case study and the approach somehow considered the works that have been done to develop CPS based on MAS, which have been discussed in several papers and articles [47–50].

Smart factories are part of the Industry 4.0 revolution where traditional factory/manufacturing approaches, methods are replaced with smart implementations. Following that, smart factories are defined as future factories where the traditional services and networks are more smart, efficient, intelligent, reliable, time-effective, and accurate thanks to the advancement in cyber and physical technologies. The main purpose of technology transformation in factories is to enhance existing services and systems as well as solve the current problems that such existing systems cannot deal with and make the production process easier, safer, smoother, and achieve high levels of speed and accuracy during all manufacturing processes. A factory can be characterized as smart depending on many factors and standards that support advanced technologies such as big data, cloud computing, IoT networking, and communication [51]. For that reason, smart solutions are proposed by many researchers and by industrial companies in different scopes of manufacturing/factories/logistics.

The main players in a smart factory are the automated guided vehicles (AGV) which are types of autonomous robots that drive and follow a predefined or marked line by using a specific type of technology like radio waves, laser vision cameras, Global Positioning System (GPS) for localization and to navigate through the pathway. Also, these robots are equipped with several sensors and other intelligent parts that make them aware of their surroundings to avoid undesired situations like collisions or crashing into an obstacle. Such robots have been deployed in warehouses like “Amazon’s Smart Warehouse” where they can guarantee a higher level of accuracy, speed, safety, and efficiency than using manual machines.

First and foremost, we used the ev3dev (https://www.ev3dev.org) operating system to develop, build, and run our Raspberry Pi-powered BrickPi (https://www.dexterindustries.com/brickpi) robots (AGVs). AGV robots comprise many physical parts such as servo motors attached to the chassis and the wheels to move the robots around the environment and ultrasonic sensor to detect obstacles and barriers. As an advantage, we equipped our robots with ultra-wideband (UWB) [52] technology provided by (https://www.pozyx.io) for indoor positioning and localization for steering and guiding the robots in the environment.

As explained before, our agent-based approach was implemented using a multi-agent paradigm, and thus, all the robots are designed and programmed as agents using the JADE platform. In the physical space (i.e., physical asset), physical robots are operated by agents which we call them (physical agents) that controls the robot's behavior, which means they have all the essential data and information that make them aware of the robot status, like battery level, the color of the packages by examining the readings from the color sensor and also can identify close objects by reading the acquired values from the ultrasonic sensor that helps the robot to avoid obstacles.

In the digital part (i.e., digital asset), physical agents are represented as digital agents and they are associated with their physical counterparts and encapsulated in the digital space. Basically, digital agents interact and communicate with each other as well as they receive the real-time data stream from the physical agents. Agents in digital space interact with the monitor agent which copies some features from the conceptual reasoning agent, and which is in charge of coordination, monitoring, giving orders, and instructions for physical agents and accordingly to the robots.

Finally, we conducted experiments to show the proof of concept of our agent-based Digital Twin implementation. Essentially, our system is comprised of two robots that resemble factory robots that work to pick up some packages from a specific location and deliver them to a target destination. Robots can detect obstacles in their way. The Digital Twin has a supervisor agent that monitors the entire system; for example, this agent manages and prevents collisions. The monitor or the supervisor agent maintains a map of the positions of all physical agents and informs the relevant agents that there is a possible collision that could happen if they are close to each other. Hence, it manages and orchestrates the collision situation by prioritizing one of the robots (i.e., the physical agent). Consequently, it continues until it is safe for the other robots to continue to their final destination. The next figure (Fig. 8) shows the setup of the robots and the physical components that compose those robots. Robots are managed and controlled by agents that retrieve and processing the data from the physical components (e.g., distance values from ultrasonic sensor, position coordinates from UWB tags) as shown in Fig. 8.

On the other hand, the next figure (Fig. 9) illustrates the agents that compose the Digital Twin in the JADE platform and how the interaction and messages are exchanged between the physical and digital agents in the Digital Twin. The graphical user interface of the JADE and specifically the Sniffer application provided by JADE platform is shown in Fig. 9.

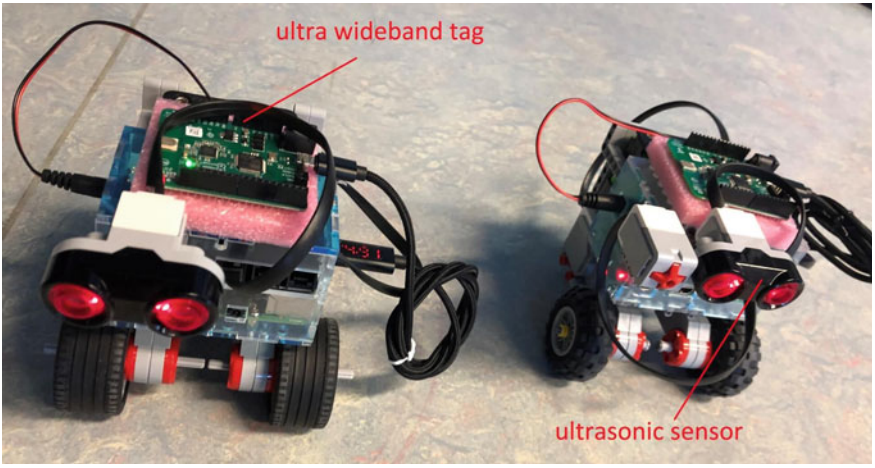

Fig. 8 Physical setup of the mobile robots

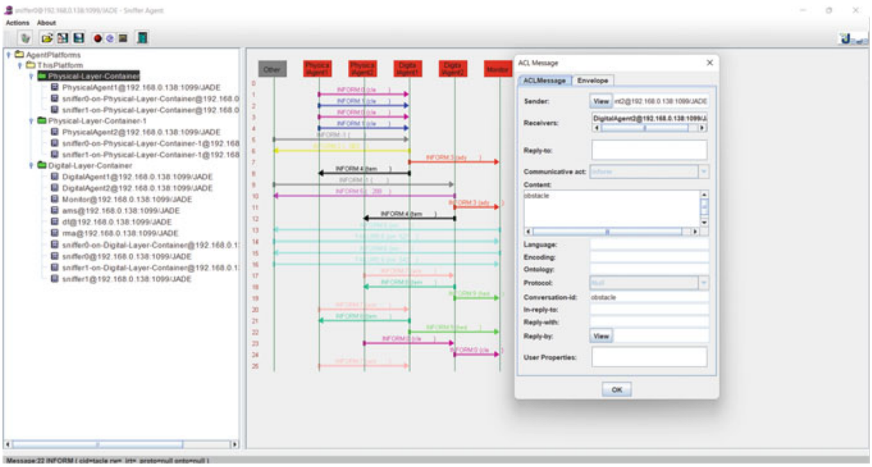

Fig. 9 Interactions between agents in the agent-based Digital Twin (JADE graphical user interface

7 Conclusion and Future Work

In conclusion, Digital Twin is a technology with very promising potential and unlimited applications. Digital Twin is getting more attention and has been applied in different scopes and domains of life. However, many researchers are trying to build and implement a Digital Twin in their various domains and areas of interest. Nevertheless, several aspects of this technology have not been covered and explored yet. In addition, Digital Twin, in principle, could be deployed in most of the domains. Nonetheless, the nature of systems in some fields can be pretty complex because of having heterogeneous elements, distributed architecture, and involves different stakeholders to compose and build up the system. Accordingly, in this book chapter, we introduce a new aspect and vision for modeling and designing a Digital Twin, and we define a determined line that we have followed to build a Digital Twin by considering and utilizing the agent-based modeling approach and multi-agent systems paradigm as the core and the essence of the Digital Twin implementation. Also, we covered several topics and discussed various concepts comprehensively in this book chapter. In addition, we introduced a reference architecture that can be used as a guideline for building physical and digital assets for the agent-based Digital Twin. Above all of that, we provided a list of tools, frameworks, and technologies that could be used to build pure agent-based CPS systems or agent-based simulations. The agent-based approach is considered to cope with and address the complexity induced by having the heterogeneous and interrelated physical and digital components in a Digital Twin, which are interacting, communicating, and negotiating with each other and constructing complex and distributed systems. Thus, intelligent and smart solutions are required to tackle such complexity.

In the direction of providing a solution and tackle this complexity, we have adopted the agent paradigm for building and realizing a reactive and cooperative multi-agent-based Digital Twin, and we have used specifically the JADE agent platform for development and deployment. We have shown how our presented approach evolved, and we have incorporated our Digital Twin implementation into a multi-robot system for a factory warehouse as a case study. In spite of the fact that agent-based modeling and simulation can be used to model and simulate certain scenarios for a system without using the physical components, and which could be quite helpful in some cases, for example, to simulate extreme scenarios that may not be possible and expensive to be conducted with the actual physical environment, up to now, in our case study, modeling and simulation capabilities are not yet provided. For that reason, we plan to extend our implementation based on the agent-based modeling and simulation approach by building a simulation environment that could be used to simulate more sophisticated and complex scenarios. This simulation function will allow us to gather and obtain deep insights and understanding of the system's behavior and its performance and how to make improvements and predict future failures.

Likewise, another extension that will be considered in our future investigations is deploying a more advanced decision-making mechanism in the reasoning agent in the Digital Twin. To realize that, the BDI software model could be considered and implemented, such that a reasoning agent can reason about a situation and decide based on the available set of beliefs and determines the most appropriate plan from the available set of plans based on the set of its intentions. In this way, the Digital Twin can adapt and adjust easily to a new situation and update the agent's libraries of beliefs, desires, and intentions according to the new context and conditions.

As the Digital Twin is a representation of the physical components, which requires high-fidelity synchronization techniques and technologies to manage the data flow from the physical asset to the digital counterparts and vice versa, and achieving such requirements, demands reliable technologies that guarantee a smooth stream of data bi-directionally in real time with minimum delays. Therefore, as another extension of the implementation, we aim to use real-time technologies for processing the high-frequency data influx. Time-series databases provide features for processing a huge amount of data as every value is associated with a processing and arrival timestamp; also, they offer the ability to store data for a long period of time as historical data that might be needed by specific agents in the Digital Twin, such as learning agents for predictive and analysis purposes.

Physical components in the Digital Twin are usually hardware, such as machines that contain sensors or/and actuators integrated into a single CPS/IoT system. Because of some physical and environmental effects, the physical component might operate inefficiently and send abnormal data "outliers", which is a type of noise in the data stream. Noisy data leads to conveying false information and then making wrong decisions and generating incorrect predictions. In such cases, methods and mechanisms for handling deviations are significantly essential to eliminate the undesired anomaly from the noisy data stream. Accordingly, technologies such as complex event processing and event streaming could be quite helpful in processing the data and detecting abnormalities. Therefore, we intend to elaborate our work using these technologies to produce reliable, robust, and efficient solutions.

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Sustainable Digital Twin Engineering for the Internet of Production

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1 Introduction

Digital twins (DTs) [1–3] have become more prevalent recently. They are used to support the design, operations, and analysis of complex systems in many domains, such as automotive [4], construction [5], medicine [6], or robotics [7], and comprise much information about the systems and processes of the twinned original system. They promise not only a better understanding of cyber-physical production systems (CPPSs) during their design time [5], but also more efficient operations of these systems [8]. For this purpose, (i) operational knowledge must be obtained from operational data, which serves to optimize the system under consideration and to develop subsequent system versions more efficiently and (ii) expert knowledge must

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_4

be made machine-processable for the operation of digital twins. Operational knowledge and expert knowledge [9] can be represented by models and, thus, automatically processed at runtime by the digital twin and the system. The operation of such digital twins therefore requires the use of software and system models at runtime, which demands that appropriate models can be formulated, analyzed, and used for interpretation or synthesis. For this purpose, the modeling languages in which these models are formulated must be explicit, machine-processable, and meaningfully integrated. Yet, most digital twins are designed and engineered ad-hoc, in a piecemeal fashion, which is costly, binds valuable engineering resources and hampers research as well as industrial application of digital twins.

Leveraging the abstraction and automation of model-driven development yields more efficient and sustainable engineering methods for digital twins. Based on interdisciplinary research conducted at the German "Internet of Production"[1] excellence cluster, we combine model-driven methods for the engineering of information systems, software architectures, and software language engineering to systematically and sustainably engineer digital twins. Within this chapter, we discuss challenges on the road to a systematic engineering of digital twins, present our model-driven approach for their engineering as well as possible implementations for different purposes. Our insights may guide researchers and practitioners to sustainable, planned, and efficient engineering and operations.

In the following, Sect. 2 introduces foundations before Sect. 3 discusses challenges in engineering digital twins. Section 4 introduces sustainability with and for digital twins, and Sect. 5 presents model-based approaches to consider sustainability with and for digital twins. Section 6 debates the related work before the last section concludes.

2 Background

2.1 Digital Twins in Production

A pillar of "Industry 4.0" [10, 11] is the digitization of participating CPPSs, processes, and stakeholders to facilitate design-space exploration, integration, verification and validation, monitoring, and the optimization of system behavior. Under the umbrella term "digital twin" [2, 3], research and industry in production have produced various approaches to modeling the digital representations of CPPSs for specific purposes. These approaches define digital twins as "digital equivalent to a physical product" [12], an "always current digital image of the production system" [13], "a mimic of a real-world asset displaying up to date information of what is currently happening" [14], "an integrated virtual model of a real-world system containing all of its physical

[1] Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) under Germany's Excellence Strategy—EXC 2023 Internet of Production—390621612. Website: https://www.iop.rwth-aachen.de.

information and functional units" [15], or "a virtual representation of an asset used from early design through building and operation" [16]. While there are many more approaches to define digital twins, most of these assume the same main functionality inherent in the definitions above: to digitally represent a system, process, or person during their operation [17].

In the following, we understand digital twins as software systems comprising data, models, and services to interact with a CPPS for a specific purpose. Therefore, each digital twin is connected (twinned) with an original system (the CPPS), which it represents and interacts with. We also assume the distinction that a digital twin has automated data flows from and to the twinned original system [2] to (i) obtain data from it to represent its behavior and (ii) to send data to it to change its behavior. These purposes can include obtaining a better understanding of the system under development or operation [1], predicting its behavior [18, 19], such as its need for maintenance, or prescribing its behavior to optimize it [8, 20].

2.2 Model-Driven Engineering

The number of software systems is continuously increasing. Additionally, they are becoming more important and more complex [21, 22]. The increasing complexity of the software of such CPPSs demands better concepts, methods, and tools that enable overcompensating this growth in complexity and harnessing their potential. An important reason for the complexity of CPPS' software is the conceptual gap between the problem domain challenges and the solution domain peculiarities. Overcoming this gap with handcrafted solutions demands enormous efforts and gives rise to *accidental complexities* [21], which are addional challenges in the solution domain that the problem domains abstract away from. For instance, to make a robot pick an object (a problem domain task), one needs to program it taking care of memory management, persisting data, or network access (solution domain peculiarities). These accidental complexities increase software engineering risks, and it is paramount to reduce these.

Model-driven engineering [21, 23] captures software development methodologies that employ models to increase abstraction and reduce the conceptual gap. Therefore, from a model-centered perspective [24], researchers and practitioners utilize models as primary communication and development artifacts for various engineering activities, ranging from design, to documentation, requirements modeling, implementation, or deployment. To be machine-processable, these models conform to modeling languages [25], which can use more abstract terminology and concepts than programming languages. Using modeling languages tailored to a specific domain, so-called domain-specific languages (DSLs), enables problem domain experts to contribute to the development of complex systems directly and without needing to become solution domain experts. Models of such languages then can be automatically translated into software artifacts leveraging code generators that embody domain expertise (e.g., how to take memory management into account properly).

2.3 Digital Shadows for Production

Digital Shadows (DSs) [26, 27] capture the idea of collecting, aggregating, and abstracting manufacturing data for specific purposes sufficiently fast, such that decisions made on this data can impact processes and CPPSs having produced the data in a timely fashion. In contrast to digital twins, digital shadows, therefore, comprise only a reduced or abstracted subset of the available data (and possibly models) to represent a system with respect to a specific purpose. For this purpose, digital shadows need to comprise various kinds of data (such as measurement data, simulation data, and models) from different sources. We abstract and aggregate the data in domain-specific and application-specific ways and augment it with necessary metadata to fulfill the DSs' purpose. Through their specific abstraction and aggregation, digital shadows can be optimal data structures to ensure timely decision-making in CPPSs.

A result of the interdisciplinary research in the German "Internet of Production" cluster of excellence is a reference model that captures the main concepts of the digital shadow. It acts as a common foundation to standardize the architecture of the relevant data held in a digital shadow. The reference model is shown in Fig. 1 as a UML class diagram and shows the reference structure, consisting among others of the main container *DigitalShadow*, the *asset* it stands for, the *purpose* the shadow fulfills and it's contained *DataTraces.* As the authors of [26] propose a purpose-driven approach for the DS, the purpose specifies what the DS is supposed to do. An asset "is an item, thing, or entity that has potential or actual value to an organization" [28, 29] and can be of physical or virtual nature. Assets are, e.g., manufacturing machines, human workers or a software component. For more complex assets, the structure can be composed into subcomponents. *Sources* (which also can be an asset) produce data of interest for our system and are, e.g., measurements or sensor data. This data is captured as *DataPoints* gathered in *DataTraces* where data points are single data entries, e.g., a table column as a snapshot at a point in time. A data trace always originates from a source (e.g., machine) and can be enriched with *MetaData* holding additional information like the experimental machine setup relevant for this data. In addition, *Models* supply a deeper understanding of the system structure and behavior or provide calculation specifications on how to aggregate and abstract the gathered data. Using this reference model, we can formalize the contextualized data aggregation in a common manner that sets the foundation to model-driven generation of digital shadows.

3 Challenges of Digital Twins

The idea of a digital shadow is subject to ongoing research [30, 31] and in the past has rarely been properly distinguished from the idea of a digital twin. Following a popular definition of digital twins based on the data flows between the original and its digital representation [2], the distinction is clear: a digital shadow follows the

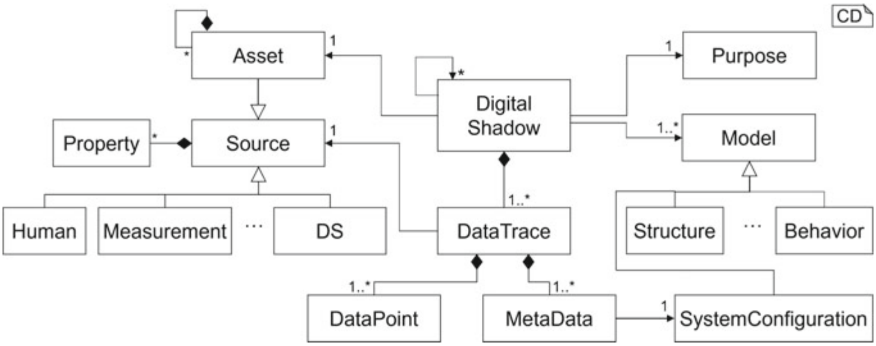

Fig. 1 Conceptual model describing digital shadow structures [26]

original system under a specific illumination (view), whereas the digital twin follows the original system as well but also may change the behavior of that system. To this end, a digital twin must be a complex software system that interacts with the original system: neither a simulation model nor some cloud-based data storage and analytics (e.g., with AWS or Microsoft Azure) alone can fulfill the requirements imposed by this definition.

This confusion about definitions is a prime reason for why research on the reuse of digital twin (parts) is not advancing at a fast pace. Despite knowing that reuse (e.g., in the form of inheritance, frameworks, libraries, or containers) is one of the prime drivers of efficient software engineering (essentially, digital twins are software), there currently is little research on reusing digital twin parts to systematically and efficiently engineer more complex digital twins from less complex ones. For instance, when composing a car chassis with a motor, the corresponding digital twins should be composed as well, or when integrating a sensor in a production system and the system into a factory, their twins should be integrated as well. Instead, digital twins are created in an ad-hoc manner.

In the literature, there are different life cycle stages of digital twins w.r.t. to the twinned system. A DT might represent the original system “as-designed”, “as-manufactured”, or “as-operated” [32]. While digital twins “as-designed” tend to be in place at design time of their corresponding original system [33], the latter two kinds of representations often aim at representing the runtime of the original system. There is little research on integrating these perspectives, which can entail that there are DTs of a system “as-designed” and “as-operated” that are developed independent from another and with little synergies between both. One important reason behind this is that this terminology hides a fundamental distinction: a digital twin of a system “as-designed” aims to represent the idealized type of that system, that is, its developers aspire to it as being a valid representation for all instances of that system, whereas a digital twin “as-manufactured” or “as-operated” needs to incorporate manufacturing tolerances and effects, as well as the wear and tear of the individual system instance. This gap demands further investigation.

In line with these challenges, there is also little research on systematically engineering digital twins together with the original system (greenfield) or after the original system has been deployed (brownfield). Both enable different functions in the corresponding digital twins. In a greenfield approach, the data required for the digital twin to perform its intended functions can be considered in the interface of the original system. However, in a brownfield approach, this might not be possible and hence, brownfield engineering of digital twins will be subject to restrictions regarding what can be observed from the original system.

4 Sustainability and Digital Twins

Sustainability is of increasing importance. It comprises social, economic, and environmental aspects [34]. Social sustainability is often related to respect for individuals, equal opportunities, diversity, and human rights. Economic sustainability is related to economic growth. Environmental sustainability has the aim to improve human welfare through the protection of natural capital. They can be seen either as distinct perspectives [35] or as a system influencing one another [36]. The further definitions of these aspects differ in the literature, but what seems to unite them is the critique of the economic status quo from different ecological and social perspectives [34]. The United Nations General Assembly has further detailed these areas and suggest 17 sustainable development goals (SDGs) with 169 associated targets [37] that should be achieved by the member states. This results in passing on the targets to companies, local authorities, and nudging of individuals.

Recent literature about sustainability and digital twins has a special focus on sustainability assessment or evaluation, e.g., for educational buildings [38], railway station buildings [5], or smart campuses [39]. Other work focuses on the improvement of sustainability performances of whole value chains due to the simulation and optimization services digital twins are able to provide, e.g., in production [40], the future development and assessment of intelligent manufacturing along a set of indicators [41] and life cycle sustainability assessment in the clothing industry [42].

To sum up these approaches, we can develop digital twins

- to support the assessment of sustainability targets due to their ability to monitor, calculate, and visualize key sustainability indicators defined by humans,
- for the simulation and forecasting of sustainability indicators if they use historic information together with forecasting algorithms, and
- which integrate digital twin services that
  - assist with responsible consumption and use in relation to created products,
  - enable simulation of different variants of digital twins before building the physical one to improve resource efficiency,
  - facilitate optimizing production processes toward waste reduction and energy saving allowing a responsible production, and
  - provide self-adaptability to improve resource efficiency.

Talking about the *sustainable development* of certain objects, none of these approaches consider that the digital twins themselves could be the objects that are sustainably developed. Model-driven engineering [43] is a promising approach to support the sustainable development of digital twins in different regards, especially when using DSLs. It leads to (1) an increased development speed and reduced development time; (2) better software quality, e.g., less bugs, because of well-defined domain-specific modeling languages, automated model checking, transformation, as well as test and test case generation, leading to reduced development time in the long run of a software system; (3) improved maintainability as cross cutting implementation aspects can be changed in one place which again reduces the development time; and (4) empowered domain experts by developing low-code platforms for the development of digital twins.

Considering human resources, these aspects are supporting sustainable development goals in the areas of resource efficiency in consumption and production and allow to reduce technological inequalities. Less development time leads to reduced energy needs for the engineering process of digital twins.

In the following section, we show some of these approaches and their impact for companies, products, and humans.

5 Approaches for Sustainably Developed Digital Twins

We have conceived, analyzed, discussed, and realized different model-driven implementations of digital twins and the process to derive large parts of their implementation from these models to reduce the effort and resources required in engineering digital twins and ultimately improve the economic sustainability of their development.

5.1 Model-Driven Engineering of Self-adaptive Digital Twins

We have realized our architecture for DTs using the component and connector architecture description language MontiArc [44]. In MontiArc, software systems are described using hierarchical components that are connected via typed directed ports. Ports describe incoming and outgoing messages of components. Components can either be decomposed, consisting of one or more subcomponents, or atomic, providing a behavior implementation on themselves.

Our digital twin architecture [1, 8] facilitates self-adaptive manufacturing by recognizing the behavior of the twinned system that diverges from the intended behavior over time. It then takes measurements to fix or mitigate this divergent behavior. We employ different modeling techniques to leverage domain expertise to improve the capabilities of digital twins for adapting to such situations.

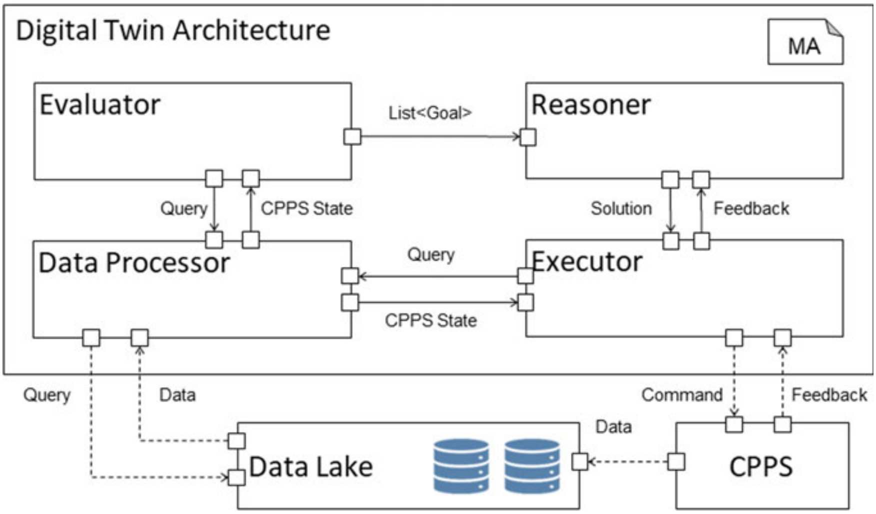

Fig. 2 Reference architecture for self-adaptive digital twins (based on [1])

The architecture for self-adaptive digital twins consists of four components each realizing a step in the self-adaptive loop (see Fig. 2):

1. *Data Processor*: It is connected to and collects relevant data from the *Data Lake*. The *Data Lake* encapsulates multiple databases storing data about the physical system and its environment.
2. *Evaluator*: It supervises the data collected by the data processor and triggers the reasoner if unintended or divergent behavior is recognized.
3. *Reasoner*: If triggered, based on data describing the intended behavior, it plans a solution to rectify the diverging behavior.
4. *Executor*: It is connected to the physical system, converts the solution of the reasoner into machine-executable commands, sends them to the physical system, and observes their execution.

To instruct and transfer domain knowledge into the digital twin architecture in a model-driven fashion, we leverage different domain-specific languages:

- *UML/P class diagrams* [45] describe elements of the domain, and their relations with each other.
- *Object-constraint language*[2] formulate constraints on the classes of the domain model.
- *Event condition action* [1] models enable domain experts to define events based on conditions over instances of the classes of the domain model. Actions define the digital twin's reaction to an occurring event. This action triggers the reasoner

[2] https://www.omg.org/spec/OCL/2.4/PDF.

of the digital twin to plan a solution for the detected event. Event models are interpreted during runtime.

- *Case-based reasoning* [8] is used for problem-solving. It reuses existing solutions from already encountered situations and computes solutions to occurring problematic situations on their basis. A case contains a condition based on the domain model, its solution, and the intended situation after applying the solution. Case similarity models define similarity metrics for cases. With that, the case-based reasoner knows based on which parameters, cases are more or less similar. Both, the case description models and the similarity models are interpreted during runtime. With more cases solved, the case base grows over time.
- *Communication specifications* enable the definition of data types that are accessible via a specific endpoint with a defined protocol. Currently, the architecture supports OPC-UA [46] and MQTT[3]as communication protocols in our communication specification models.
- Query definitions are specifiable via an *expression language*. It comprises the expressions such as maximum, minimum, or simple mathematical expressions. The query language is employed for collecting and aggregating data in digital shadows from sources such as the *Data Lake*.

For deriving models of the mentioned modeling languages, existing engineering models of the CPPS can be reused. To this end, CAD, kinematics, material flow, control models, and others can be employed to derive events and parts of the domain model. This lowers the initial effort in developing the digital twin. The automatically derived models can be enriched by domain experts with further details.

Regarding sustainability, our digital twin enables humans to define sustainability via the modeling of events and case-based reasoning goals, and the respective architecture components responsible for monitoring and calculating indicators based on these models enable the assessment of sustainability targets. Furthermore, our digital twin is self-adaptive to improve efficiency and save resources by optimizing the production process.

Sustainable development is achieved through increased development speed by employing modeling languages and models for different aspects of the digital twin. These modeling languages are domain-specific, and, thus, empower domain experts to configure the digital twin to their needs through the reuse and semantic reification of common concepts of the model-driven development of digital twins.

5.2 Generating Digital Twin Cockpits

Digital twins require an interface for inspection and control. We define a digital twin cockpit as follows:

"A digital twin cockpit is the user interaction part (UI/GUI) of a digital twin.

[3] http://mqtt.org.

It provides the graphical user interface for

1. visualizations of its data organized in digital shadows and models, and
2. the interaction with services of the digital twin, and thus
3. enabling humans to access, adapt, and add information and
4. monitor and partially control the physical system [47].”

Key aspects for a digital twin cockpit, such as the data structures and user interfaces, can be described with models. Using the MontiGem generator framework [48], developers produce a web application that can serve as a cockpit for a digital twin. It can be connected to the reference architecture for self-adapting digital twins [49]. The target application is a server-client architecture connected to a relational database (see Fig. 3). To realize the digital twin cockpit, a data structure and a UI generator are used. The first one generates the infrastructure that connects both the database and the client to the server. Based on the input domain model, it provides a multitude of interfaces to perform CRUD operations in the database as well as process client input in a systematic, authorized, and authenticated manner. The components created by the UI generator are fitted to the provided interfaces from the data-structure generator and thus provide implementation for detailed views on the current data available to the back end.

This approach supports reusability of components and models, due to its model-driven design, enabling sustainable methodologies for software development. With

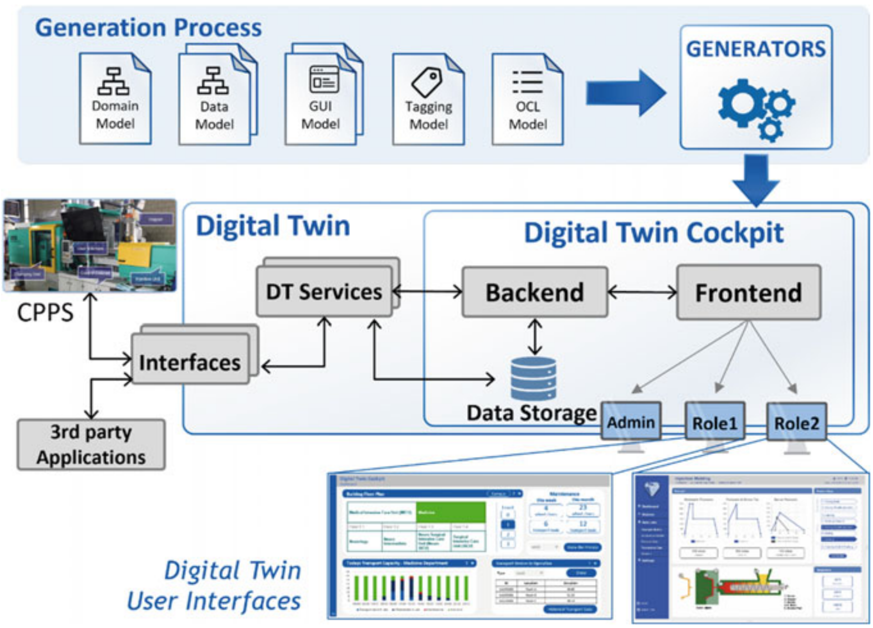

Fig. 3 Artifacts of the MontiGem generator framework used to generate a digital twin cockpit with multiple interfaces according to each role of the end user

this approach, the developer can rapidly implement digital twin cockpits that are easily adapted with custom logic and extended with further complex data structures.

5.3 Process Prediction as a Digital Twin Service

Using process mining techniques, we are able to analyze event data from physical systems and extract information related to processes, e.g., discover process models [50]. To systematically improve the operation of digital twins, we can use these techniques: Process discovery from runtime data of the physical object, conformance checking if the processes of the physical object are running as planned, and simulations or process prediction using process models where changes in processes in the long run can be foreseen [18].

We need to additionally provide functionality to handle explicated processes of the physical object and its context in the digital twin cockpit, which leads us to the concept of *process-aware digital twin cockpits*. A process-aware digital twin cockpit "is a digital twin cockpit that additionally provides functionality to handle explicated processes of the physical object and its' context" [47]. To integrate process prediction and conformance checking services allows us to analyze the processes of the CPPS based on real-time data during runtime of a self-adaptive DT.

We envision a model-driven DT architecture that uses models at runtime and incorporates process mining techniques (see Fig. 4) covering the following six steps:

1. **Generation of the DT**: Using domain knowledge of experts and from engineering models, e.g., AutomationML, CAD, Modelica, SysML, we can create a set of application-specific models such as class diagrams for the structure, or process models representing the machine processes or processes of related

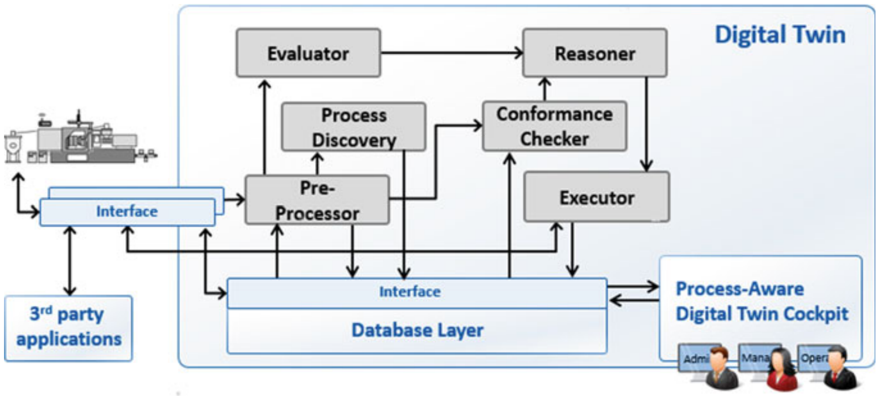

Fig. 4 Process discovery services as well as conformance checking services as parts of a digital twin visualized in process-aware digital twin cockpits

humans. Together with application-independent models, e.g., the DT architecture or the basic digital shadow or process model structure to handle models during runtime, these models are used as input for code generators to generate a DT (see Fig. 4).

2. **Configuration of the generated DT application**: We have to add relevant runtime models and specify digital shadow types. We need to know for which purpose the DS is needed, which data accessed by a fully qualified address with respective data points and metadata, should be chosen and how it should be aggregated.
3. **Initialization of DSs**: Using the DS types, the DT computes relevant DSs from the latest data and stores them for further processing.
4. **Process discovery**: By applying process discovery algorithms on data transformed into event logs, we can discover how processes run in the real environment. They can be stored and visualized in the DT cockpit.
5. **Runtime analysis**: In a next step, discovered processes can be compared to processes-to-be in conformance checkers which allows to identify problems and reconfiguration needs of the physical object. Moreover, they can be used for process prediction.
6. **User interaction**: At runtime of the DT, human users can view data and processes about and interact with the physical object and the provided services of the DT.

These functionalities allow us to create DTs supporting sustainability, e.g., to compare as-is-processes with to-be processes regarding their use of materials and production of waste.

5.4 Low-Code Platforms for Model-Driven Digital Twins

Digital twins are highly complex software systems that require a high amount of development resources over a long time period. A high number of the components of a digital twin are either systematic or can be categorized as "boilerplate code", thus enabling a good application of generative approaches. Low-code development platforms (LCDP) aim to operate on similar principles as generators, by providing a large amount of implementation based on simple configurations and models.

The generator framework MontiGem [48] can be used to create a LCDP that enables the developer to configure and finally generate a digital twin [51, 52] (see Fig. 5). MontiGem is extended with LCDP language plugins and a model library covering multiple use cases. This enables the generation of a LCDP that provides the developer with user interfaces to configure the multiple models that ultimately define the digital twin. Once configured, the same framework can be used again to generate further digital twins for the same use case.

This approach combines the benefits of generators and LCDPs to rapidly produce multiple digital twins that can be used with similar configurations, e.g., on multiple

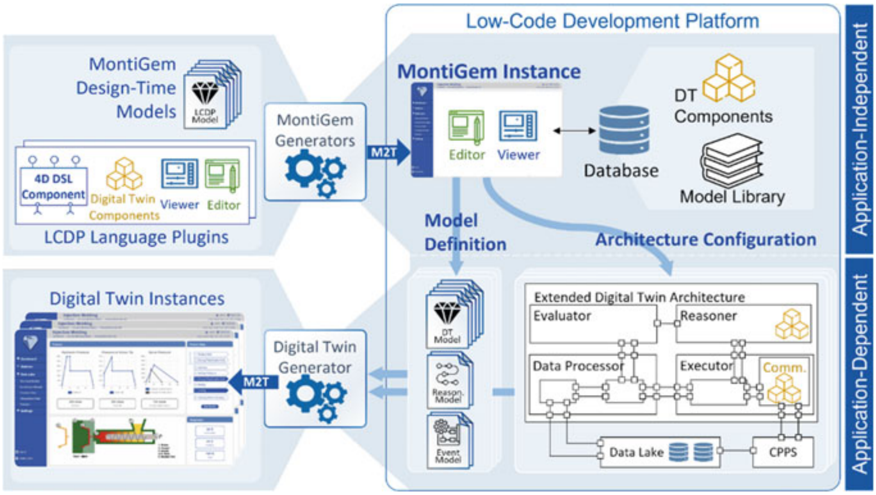

Fig. 5 Process in which MontiGem is used to generate an LCDP, which in turn is used to configure and control digital twins

machines on the same factory floor. This approach reduces development resources and, thus, supports the sustainable development of DTs.

5.5 Ontologies and Digital Twins

Ontologies [53] provide the terminology to express domain knowledge and make this locally gathered knowledge and its semantic concepts globally available. Ontologies, similar to UML class diagrams, describe structural parts of (production) data as well as their semantic interconnection. Reasoning and inference rules are used to derive new knowledge on a given data set. One of the driving purposes of ontologies is the ability to reuse domain knowledge: A detailed ontology, published by a group of researchers, can easily be repurposed by others allowing for combining ontologies to larger vocabularies tailored to a specific domain.

In our digital twin architecture, we can use ontologies to enrich the domain's structural part described by annotating additional information to classes and attributes in the class diagram. Commonly used concepts in production, such as sensors or material properties, are already defined in ontologies [54] and provide the development process of DTs with a formally defined vocabulary. This way, we can connect locally specified structure elements to globally valid concepts in a model-driven manner, reuse pre-existing components, and provide an easier comparison to other use cases.

5.6 Assistive Services Within Digital Twins

Digital twins could provide *intelligent assistive services* supporting human operators, e.g., they could assist operators in production processes in making the best possible decisions using human-behavior goals [55]. This is important, as operators have to handle an increasing amount of detailed information. Within not fully automated production steps, we can use assistive services within DTs to analyze a current task, identify next tasks, and suggest their (semi-automated) execution [56]. These intelligent assistive services [57] (1) provide support for human behavior tailored to specific situations, e.g., in case of adding resources in the production process or making repairments. (2) The support is based on stored and real-time monitored structural context and behavior data. Within DTs, especially ones which explicitly handle process information, large parts of the data are already available, e.g., process models for describing the physical object or relevant data and parameters. Missing aspects which have to be additionally modeled for realizing assistive services are support processes including user interaction. (3) The support is provided at the time the person needs it, e.g., when a human user has to operate with the CPPS, or when the person requests it, e.g., via interaction components of the digital twin. To realize such assistive services within the system architecture of DTs requires additional interaction components for user communication and assistive visualization and the internal handling of process models during runtime. Process models can be defined manually or one can use methods for the semantic annotation of user manuals [58] of production machines to automate the setup of assistive information.

To incorporate assistive services within digital twins support two different aspects of sustainability: Within the production process, assistive services can be used to provide users step-by-step support to improve key sustainability indicators. If products are delivered to customers together with a digital twin of the product, assistive services can be used to support customers with improving key sustainability indicators related to the use of the product.

5.7 Calibration and Adjustment of Simulation Models of Digital Twins

The simulation models used in virtual commissioning are suitable as a basis for digital twins of production systems, as they represent the behavior of these systems and are often already available from the development phase. These "as-designed" simulation models represent the respective production system in a generalized way [59, 60]. However, a digital twin requires simulation models that represent the real system; an "as-operated" model. If the "as-designed" models are used without any adaptations to the real system, there would be considerable discrepancies between the behavior of the general simulation models and that of the concrete production system. For this reason, they cannot be used directly within the digital twin. Therefore, efforts are being made to synchronize the behavior of the simulation model and the real production system so that the model can become part of a real "twin" of the concrete production system instance.

So far, simulation models for virtual commissioning are only used in the development phase of production systems to test the control code [61]. With regard to the digital twin, there are some publications in which discrepancies between the simulation model and the real system are investigated and compensated for specific aspects of the digital twin [62–65]. For this, the simulation models must be adapted to the reality of the concrete CPPS instances, whose behavior increasingly diverges from the idealized assumptions of these simulation models due to tolerances in the structure, environmental influences or wear—"as-operated". However, the issue of how to convert the "as-designed" models into "as-operated" models is not addressed. The initial "as-designed" simulation models, thus, increasingly deviate from the reality of the actual system behavior, whereby they lose their predictive capabilities and analyses of this leading to erroneous conclusions. During commissioning, the general simulation models of the system must therefore be transformed into instance models of a concrete, physically constructed system in order to continue enabling useful analyses. Currently, however, changes through adaptation or wear and tear to the (often long-lived) CPPS are not represented in the digital twins or in updates to their simulation models, so that control and simulation of the CPPS assumes outdated assumptions encoded in the models and information relevant to the development of future versions of the represented CPPS is lost [66]. This is essentially a modeling challenge [66, 67].

To solve this modeling challenge, a sustainable methodology needs to be developed to (partially) automatically transform the general simulation models of CPPS into precise instance models during commissioning. For this purpose, it is investigated how different modeling concepts, methods, and tools of model-driven software development, such as software language engineering [56, 68, 69], model transformations [70] and self-adaptive digital twins [9, 8, 44], can be suitably adapted and combined in a domain-specific way.

6 Related Work

In the development process of production plants, it has become common for domain experts to design digital twins as simulation models with the purpose to develop and test the control code of the plant at an early stage. The real control hardware and communication medium (field bus system) are used for this as a hardware-in-the-loop simulation. It is advantageous if the simulation models are calculated in the real-time cycle of the communication periphery in order to be able to carry out the most meaningful tests possible. This process is commonly referred to as virtual commissioning. In most cases, it is sufficient to model simple kinematics and material flow to positively influence control code development. However, this does not apply to the use of simulation models in an operational simulation. In some cases, highly accurate simulation models are required that cannot be calculated in real time. Co-simulation has established itself for these cases [71]. There are also other potentials of these simulation models that go beyond pure virtual commissioning, such as control optimization by means of macroscopic material flow models [72] or the support of control development by means of AI [73–75]. These aspects make these simulation models interesting as a possible component of digital twins.

Recently, various digital twin platforms have emerged [76]. They aim at supporting developers in creating digital twins and digital shadows and provide tooling support for different aspects of a DT. Numerous DT platforms already exist from various vendors, e.g., by IBM,[4] Oracle,[5] Siemens,[6] Amazon Web Services[7] [77], Microsoft Azure[8] [78], and Eclipse.[9] We already compared the latter three platforms in terms of functionality [79]. All three of the investigated DT platforms provide comprehensive infrastructure for defining data structures for the data exchanged between physical and digital twins. For this purpose, they even provide modeling languages. However, models of these languages are not interoperable and restricted to their platform. Also, they miss standardized interfaces to enable composition of digital twins, or command models that enable interaction with other value-adding services, such as simulations or prediction. Because the platforms only provide modeling techniques for structural modeling, compared to our solution behavior, i.e., the communication, evaluation, and reasoning, of the DT cannot be defined in a model-based way and requires hand-written code to be deployed to the used cloud platform. This requires skilled software engineers, whereas our approach does not require programming skills from domain experts. Microsoft's and Amazon's DT platforms are part of their cloud ecosystems providing the advantage that their DTs can use machine learning capabilities, data processing algorithms, and CI/CD functionalities provided by their ecosystem. However, our approach to digital twins can be easily deployed to these platforms, enabling users to experience the advantages of these platforms. Our approach could be extended with interfaces to integrate features of the platforms.

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7 Conclusion

In this chapter, we have presented a collection of methods for the sustainable model-driven development of digital twins. These methods are based on our understanding of digital twins as software systems that comprise data, models, and services enabling interaction with a CPPS for specific purposes. Leveraging models as primary development artifacts supports (a) the sustainable engineering of digital twins as well as (b) the engineering of sustainable digital twins, i.e., to leverage monitoring, controlling, and optimizing the behavior of CPPSs through their digital twins. The methods can be applied to digital twins in a variety of application domains and shall guide researchers and practitioners in the conception, engineering, and operations of digital twins.

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Digital Twin Use Cases

Fog-Connected Digital Twin Implementation for Autonomous Greenhouse Management

Hakkı Soy and Yusuf Dilay

1 Introduction

During the last decade, as a result of ongoing digitalization, many industries have been improving or upgrading their existing technologies in light of the increased utilization of automation and digitization to gather, analyze, and manage the data streams. In the manufacturing industry, all these emerging trends that enable the reconstruction of the existing ecosystems are called as Fourth Industrial Revolution, or shortly Industry 4.0 [1]. Industry 4.0 mainly aims to create 'smart' manufacturing lines and factories, wherein the operations are made intelligently to boost productivity and efficiency through modern technological innovations. Besides the manufacturing industry, thanks to advancing technologies, the digital transformation wave has also reshaped the way of doing farming in a big way [2]. The reflection of the Industry 4.0 paradigm on agricultural practices, known as Agriculture 4.0, offers farmers to collect, process, and analyze data timely and accurately through the use of advanced farm management systems. No doubt, empowering the capability of decision-making with regard to planting, fertilizing, and harvesting of crops can contribute significantly to increasing yield and quality as well as saving resources when cultivating crops [3, 4].

The undesired weather patterns (i.e., frost, limited sunshine, extreme heat, drought, and flooding) usually have a negative impact on crops yields [5]. Controlled-environment agriculture (CEA) is a smarter approach to ensure the best harvesting conditions by precisely controlling plant growth conditions and optimize use of resources. In regions and/or seasons where it is not suitable to keep the plant growing

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_5

to achieve a high level of productivity, a building that can provide optimal conditions for crop growth by controlling the environmental factors is called a ‘greenhouse’. Greenhouses are naturally surrounded by translucent plastic or glass walls that allow the sun’s rays to pass through them. Thanks to the microclimate created in the indoor environment in a greenhouse, it is possible to protect against the unfavorable climatic conditions in the outdoor environment is provided [6, 7]. Indoor microclimate control is essential for greenhouse cultivation, and it mainly depends on keeping the lighting, ventilation, irrigation, and heating operations at the optimal level. Modern greenhouses comprise several subsystems, which are operating independently of each other to control the indoor environmental conditions. When optimal control is applied, the crop yield increases and the production costs are also reduced [8, 9].

In a typical greenhouse, the temperature and humidity parameters directly affect the processes of respiration, transpiration, absorption, and translocation of plants and also indirectly change the growth rate of the crops. Hence, environmental conditions must be kept at desirable levels to keep plants healthy [10]. Besides, plants need water to continue their development. Insufficient irrigation causes economic losses due to the decrease in product quality and production capacity. On the contrary, if too much water is applied, the plants will be damaged. Over-irrigation disrupts the pH balance in the soil and also changes the oxygen and nitrogen concentrations [11, 12]. Unfortunately, the ideal environment (i.e., temperature, humidity, light) and soil (moisture, pH, oxygen, and other mineral nutrients) conditions for appropriate growth differ from plant to plant. Moreover, when considering different plants/crops that exist in the same greenhouse, decision-making for when to irrigate and how much water to apply are difficult problems to overcome for irrigation management in greenhouses [13].

Nowadays, thanks to the development of innovative information systems and the support that comes from modern communication technologies, it is possible to build a ‘digital twin’ of any physical space that includes a set of processes [14, 15]. A digital twin is a digital representation of a physical object, process, or overall system that is used for various purposes in buildings, transportation, and industrial plants [16, 17]. Actually, the digital twin is not a new concept, but it has not been widely adopted in earlier decades as a result of insufficient technological maturity. Essentially, a typical digital twin requires the virtual model of the connected physical entity, communication infrastructure, and enabling technologies that are used to collect, analyze, and store the data streams from distributed sensors. Internet of Things (IoT), artificial intelligence (AI), cloud computing, and big data technologies are indispensable tools to overcome the challenges due to the gap between the physical and virtual worlds [18]. Cyber-physical system (CPS) architecture provides an integrated and compatible framework for all these enablers by combining hardware and software resources [19].

Considering the successful applications in the industry, the employment of the digital twin technology can be an excellent complement to the management of smart greenhouse facilities [20]. Especially, the autonomous digital twin implementations help to remotely monitor the behavior of environmental parameters and allow to intelligently control the operation of actuators, i.e., motor, pump, valve, heater, and fan in a greenhouse. Beyond that, through the empowered computation, the insights gleaned from simulations help to improve physical performance, better manage costs, predict the risks in the future, and take required measures to avoid them [21]. Digital twin applications are usually run on cloud server to get more computing power and storage capacity. It should be highlighted that the digital twins must be designed as real-time systems to immediately reflect changes in the real world. However, in some scenarios like smart farming, a strong and stable Internet connection is not always available for transferring the data collected from end devices to the cloud server. As a solution to this problem, it can be considered that the implement the digital twin on the edge devices or fog servers. Due to the limited computing resource at the edge of the network, the fog computing emerges as a most relevant approach [22, 23].

This chapter introduces an autonomous digital twin-based CPS framework that enables remote monitoring and control of the microclimate and irrigation conditions in a typical greenhouse environment. In our implementation, we have adopted a wireless sensor/actuator network (WSAN) architecture formed by sensor and actuator nodes besides the coordinator nodes that connect them directly to the local server. In order to intelligently manage the greenhouse environment, we have also created a fog-connected digital twin software that enables the analysis of the collected data between the edge and cloud. The experimental validation of the proposed approach has been performed in the pilot greenhouse of the Karamanoglu Mehmetbey University, Karaman Province, Turkey. The hardware design, communication protocol, and digital twin implementation of our study were explained in detail in the following sections.

2 Related Works

In recent literature, a considerable amount of research has been made to develop digital twin-based smart farms that can improve quality, productivity, and sustainability.

Verdouw et al. [24] have investigated the contributions of digital twin to the development of smart farming applications. The authors review the recent literature on the popular databases to find out the definitions of key concepts. After that, a conceptual framework has been presented for designing and implementing digital twin in farm management. The introduced framework includes two different models, namely control model and implementation model. Additionally, their framework was applied to case study to confirm its compliance. According to that, a monitoring digital twin is connected in (near) real time to its physical twin and it is used to monitor the operating conditions of the actual state via a digital representation, whereas an autonomous digital twin operates autonomously and fully controls the behavior of physical objects without intervention by humans. An autonomous digital twin can be considered as a self-adaptive system that can learn about its environment, self-diagnose its own service needs, and adapt itself to users' preferences. Clearly, autonomous twins create a complete control loop, but they run based on decision support models and control norms of humans. Besides them, a predictive digital twin can forecast the future states and behavior of physical objects using data analytic methods. The prediction is done with collected sensor data that correspond to the current and historic state of the physical objects.

Pylianidis et al. [25] have realized a literature review of digital twins in agriculture research published between 2017 and 2020. This study has identified 28 use cases and compared them by considering reported benefits, service categories, and technology readiness levels to assess the level of adoption in agriculture. The authors emphasized that a key aspect of digital twin is information fusion from several heterogeneous sources. When the information fusion is combined with the continuous nature of operations, a digital twin can depict the complete picture of the past and the current state of the physical system as well as allow to estimate the future states. Moreover, a roadmap was provided for the development of agricultural digital twins with fewer components and simpler functionality. As mentioned there, on a fundamental level, a digital twin monitors the current state of the physical system (e.g., microclimate of a greenhouse). A slightly enhanced digital twin performs control operations (e.g., fans and windows in a greenhouse) in addition to monitoring service by adding actuator components. Further enhancing digital twins with model-based simulations can predict the state, behavior, and needs (e.g., excess soil moisture risk due to over-irrigation) in the future.

Alves et al. [26] have created a digital twin to control the irrigation system by leveraging the technologies developed during the 'Sensing Change' and 'Smart Water Management Platform (SWAMP)' projects, which aims to develop a soil moisture probe and IoT platform for water management, respectively. The Sensing Change project consists of a monitoring station, a smartphone application, and a cloud application for data visualization and analysis. The SWAMP platform can be configured both to do the decision-making process completely by the farmer or to apply AI for automated decision-making. The digital twin provides a graphical interface, shows the information collected using the IoT platform, and manages the operations like irrigation.

Today, besides the popularity in open-field agriculture, several digital twin applications have also been introduced for greenhouse management.

Chaux et al. [27] have introduced a digital twin architecture for CEA applications. A prototype greenhouse model has been utilized as a case study for the design and verification of their proposed digital twin architecture. The main aim is to optimize productivity by using a bilateral communication and simulation model. The required optimization has been achieved in the local device. Then, the optimal crop treatment and climate control strategy have been transferred to the controller for its implementation through a gateway. The EnergyPlus (energyplus.net) and DSSAT (dssat.net) were selected as simulation software to optimize the crop microclimate and treatments related to crop management, respectively. The authors have made a substantial contribution to our understanding of how the digital twin helps farmers to develop sustainable agriculture.

Cao et al. [28] have proposed a digital twin-based smart agriculture solution, called as iGrow, for autonomous greenhouse control. The authors' study contains three parts, namely the formulation of the autonomous greenhouse control problem as a Markov decision process (MDP), designing the neural network-based simulator to simulate the complete planting process of an autonomous greenhouse, and creation of the closed-loop bi-level optimization algorithm to dynamically re-optimize the greenhouse control strategy with newly observed data during real-world production. Besides the simulation experiments, iGrow has also been tested in real scenarios, and the experimental results have validated the effectiveness of the proposed approach in autonomous greenhouse simulation and optimal control. The obtained results from the tomato pilot project in real autonomous greenhouses have shown that iGrow significantly increases crop yield (+10.15%) and net profit (+92.70%) with statistical significance compared to planting experts.

3 System Model

The proposed smart greenhouse management system comprises both physical and cyber spaces. The physical space relies on a wireless network of sensor and actuator nodes, known as WSAN, that are distributed over at certain locations in a greenhouse. The sensor nodes (SNs) are categorized into two different groups based on their sensing abilities. A weather SN is capable of sensing the temperature and humidity of the air inside the enclosed greenhouse environment, while a soil SN detects the moisture level on the roots of the plant. Similarly, the actuator nodes (ANs) are also categorized into two different groups based on their functions. A weather AN controls the ventilation fan to remove warm and moist air and replace it with drier air. Withal, a soil AN regulates the position of solenoid valve to satisfy the soil moisture requirements of individual crop types. Besides them, there are one or more coordinator nodes (CNs) to manage the distributed sensing and control functions in harmony with each other. Each CN has also a wireless link to the root node called as base node (BN). The BN connects the heterogeneous nodes in physical space to the local server in cyber space. The digital twin software runs in local server and describes the virtual replicas of all physical assets on the real world of the computer. Figure 1 shows the proposed smart greenhouse management system with all components.

Our digital twin implementation mainly aims to autonomously control the ventilation and irrigation operations without human supervision. According to that, the digital twin continuously collects data from the real greenhouse environment via the SNs and aggregates them to produce intelligent decisions. Then, it also triggers the required actions via the ANs to keep the environmental conditions ideal for plant growth. The optimal weather and soil conditions of individual crop types are held in the digital twin. The digital twin configuration interface allows to pair the SNs and ANs to each other with respect to their locations and functions. The role of the CN is to transfer the sensor readings and control commands in both directions between the cyber and physical systems. The SNs are battery-powered devices with constrained resources, and each of them is equipped with the necessary electronics to sense the environment. On the contrary, the ANs have more powerful resources, and they are

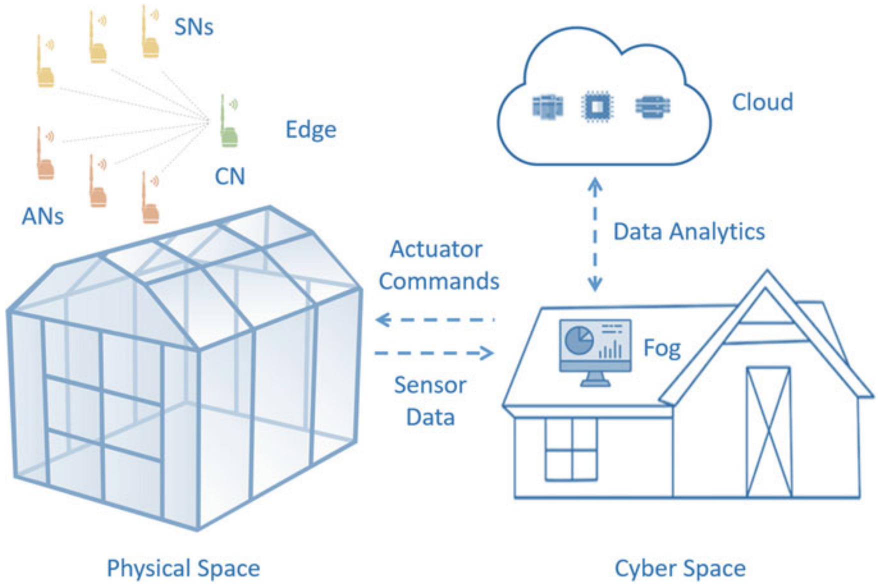

Fig. 1 System model of proposed digital twin implementation for smart greenhouse management

often supplied with the main power supply. Since the CN plays a critical role to integrate the physical and cyber spaces, it is also equipped with a power supply unit to ensure the uninterruptable operation.

4 Experimental Study

In this section, to validate the applicability of the proposed system, we present our experimental study. Figure 2 shows the view of the greenhouse in Karamanoglu Mehmetbey University used for our digital twin implementation.

4.1 System Setup and Method

The proposed WSAN-based greenhouse management system automatically controls the ventilation and irrigation operations to respond the changes in the environment. In our system setup, the soil SNs have been distributed on the ground, while the weather SNs have been placed at different zones in the greenhouse. To meet the ventilation needs, the weather ANs have been distributed inside the greenhouse to drive the air circulation fans. When combining the related weather SN/AN pairs, it is possible to provide an independent ventilation control function to a plurality of climatic zones

Fig. 2 View of the test greenhouse in Karamanoglu Mehmetbey University Campus

inside the greenhouse. Besides, the soil ANs manage the irrigation distribution by triggering the solenoid valves. The drip irrigation method has been preferred due to its water-saving advantage by allowing water to drip slowly to the roots of plants. So, the entire field is divided into laterals (water supply pipes), and one pair of soil SN/AN arranged on each lateral. The drip irrigation method eliminates the surface runoff and provides uniformity for the water distribution. Also, it decreases the incidence of plant diseases that can occur with the use of overhead sprinkler irrigation.

4.2 Hardware Design

In the hardware design of the nodes operating in the WSAN, the Arduino platform has been used due to its low cost, versatility, and extensive open-source support. On this basis, all of the SNs and ANs have been built on the Arduino Uno board using several electronic components. Arduino Uno has a Microchip ATmega328P microcontroller with 2 KB of SRAM, 1 KB of EEPROM, and also 32 KB of flash memory to store the program codes [29]. Additionally, the low-cost nRF24L01 transceiver module has been also used on hardware design of the SNs and ANs to allow wireless networking in the WSAN. The nRF24L01 transceiver operates in the unlicensed 2.4 GHz, and the band baud rate can be changed from the 250 kbps to 2 Mbps [30]. To reach long distances from greenhouse to local server, the CNs and the BN have been equipped with an nRF24L01+ transceiver module, which has a power amplifier (PA), and a low noise amplifier (LNA) as well as an external antenna on board [31].

The weather SN includes the DHT11 sensor (currently replaced by DHT20) to measure the temperature from –20 to +60 °C with an accuracy of ±1 °C and relative humidity ranging from 5 to 95% with an accuracy of ± 5% [32]. The soil SN is equipped with a SEN-13322 resistive type soil moisture sensor, which provides data depending on the amount of water in the soil. Principally, when the water content increases in the soil, the conductivity also increases between the pads of the sensor. The variation of conductivity also changes the soil resistance [33]. Figure 3 shows

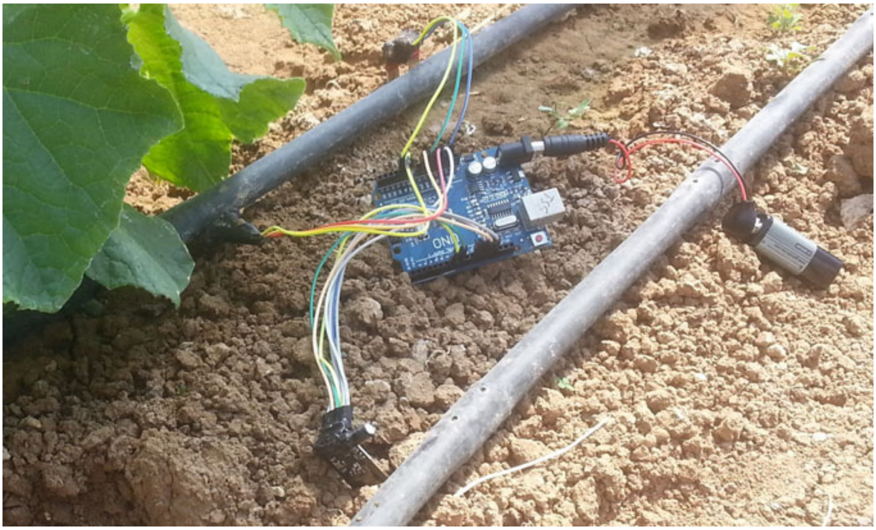

Fig. 3 View of the soil SN on the Arduino Uno board

the soil SN with all hardware components. The weather AN has a driver circuit (with BDX53C transistor and 1N4007 diode) to rotate the air circulation fan with a 12V DC motor. The soil AN is connected with the AQT12SLT ordinary two-way solenoid valve, which operates between fully open and fully closed states. When the supply voltage (6/9/12/24/36V DC 110/220V AC) is applied to solenoid valve's terminals, it allows the water to flow through drip pipe [34]. Figures 4 and 5 show the soil AN and CN with all hardware components, respectively.

4.3 Network Architecture and Communication Protocol

A reliable connection is an essential requirement of the digital twin applications to ensure robust communication between the physical and cyber spaces. Hence, the connectivity is a cornerstone to establishing the successful CPS platform in the proposed smart greenhouse management system. Although the wired connectivity provides faster and more reliable data transmission, the installation of the cabling infrastructure is not possible in farmlands due to the significant additional costs. On this basis, we have established a wireless network that can enable the flow of sensor data from the greenhouse to the local server and also actuator commands from the local server to the greenhouse.

To meet the system requirements, our privileged design focus is on creating the WSAN architecture which has simplicity and scalability. But, due to the nRF24L01 transceivers' limitation on the number of connections, it is not very easy

Fig. 4 View of the soil AN on the Arduino Uno board

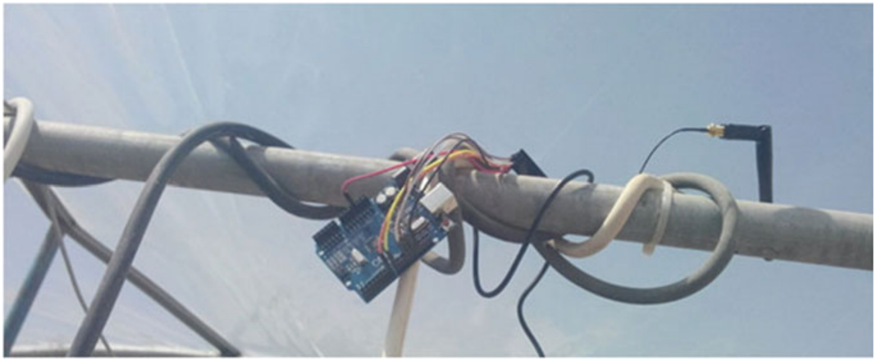

Fig. 5 View of the CN on the Arduino Uno board

to extend the wireless network with star topology. In the datasheet of the nRF24L01 transceiver [30], it is clearly stated that there can be up to six modules configured as a transmitter, which can actively communicate with one module configured as a receiver. So, the receiver opens six data pipes (0–5) and transmitters links to one of these pipes. By considering the star network restrictions imposed by the nRF24L01 module, we preferred to use cluster-tree topology to maintain the scalability in our WSAN implementation.

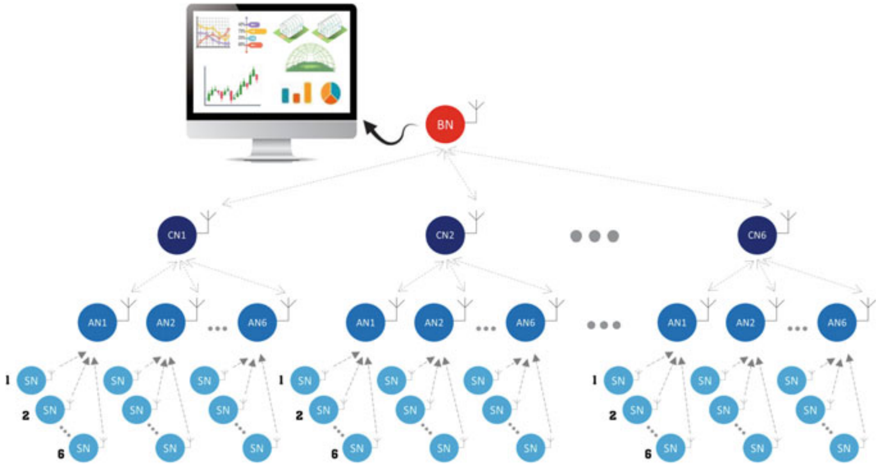

Fig. 6 Cooperative WSAN architecture for sensor-actuator coordination

The sensor-actuator coordination is an absolute aspect of WSAN-based systems to establish the wireless links for the transmission of monitoring data and control commands [35]. In our WSAN design, we used the cooperative architecture proposed in [36] to provide the sensor-actuator coordination. According to that, the SNs transmit their measured data of interest to the ANs directly and the ANs forward them to the CNs. Finally, the CNs transfer all the sensor readings to the local server via the BN, which is a common sink acting as an interface between the physical and cyber spaces. The digital twin application evaluates the collected data and sends the commands through the CNs to control the operating status of the ANs. Figure 6 depicts the data flows between the nodes by using sensor-actuator cooperation.

In the closed control loop, the SNs periodically report sensed data to the ANs and they stay in sleep mode at all the rest of the time to save energy. On the contrary, the ANs and CNs are kept continuously awake by switching between transmit and receive modes to listen and relay data from the SNs. Since the agricultural processes are not time critical, we have found it appropriate to extend the sampling period for sensor reading and actuator triggering in a way that does not block each other. Thus, it was assumed that the reporting period is fixed at five minutes and each SN reports a single data packet per period. After the aggregation and processing of up-to-date data, the ANs are triggered when the setpoints are exceeded in an event-based manner.

The data exchange between the nRF24L01 transceivers is provided by Enhanced ShockBurst^{TM} (ESB) protocol, which is developed by Nordic Semiconductor for ultra-low-power wireless applications [37]. Actually, ESB protocol has a baseband MAC protocol engine embedded in transceiver chips to define a clear channel access algorithm. Both the nRF24L01 and nRF24L01+ transceivers support the ESB protocol, and they use the generic packet format frame structure defined by it to ensure the transmitted packets can be received by the correct receiver. The RF24Network is a complete library for creating a WSAN with cluster-tree topology and cooperative sensor-actuator coordination [38]. In our implementation, by using the addressing scheme, we have configured all the nodes in a way that can directly communicate with their parent and children nodes. So, bidirectional information flow has been established between the WSAN operated in the greenhouse and the digital twin application on local server.

4.4 Digital Twin Implementation

Essentially, a digital twin is a software that provides a live representation of the real world for visualization, data analytics, and decision-making. Considering the application requirements of greenhouses, we have developed the digital twin application by using Visual C# language in Microsoft Visual Studio.NET Integrated Development Environment (IDE). The developed application consists of several graphical user interfaces (GUIs) that are connected to the database. It enables to flow of data in both directions between the virtual and physical parts. Clearly, the sensor data feed into the digital twin so that the current status of the physical world is updated. When the configured thresholds are exceeded, the alarm alerts are displayed on the dashboard. According to the results of simulations run on the digital twin, appropriate decisions are taken to control the actuators' positions.

In our system setup, the management of ventilation and irrigation operations is controlled by the digital twin application, which enables us to define all the crop types and their ideal growing conditions as well as placement in the greenhouse. The developed application allows configuring the system with different needs in different zones. In this way, the weather and soil SNs have been paired with suitable weather and soil ANs that are close to their duty profiles. Thanks to this collaborative operation, even if different plants are grown in the greenhouse, it is possible the independent control of fans and solenoid valves in different zones/laterals. So, the sufficient amount of water is applied to the plants, and the irrigation is terminated when the water will reach the roots by going drop by drop. The ventilation starts when fresh air is needed by plants. Figures 7 and 8 show the monitor and control functions of our digital twin software, respectively.

Besides visualization and data-driven decision-making, the developed digital twin has also the ability to make statistical data analytics (i.e., time-series analysis, descriptive statistics) to generate insights by detecting patterns of anomalies from large volumes of data. The obtained predictions can be helpful to provide early detection of plant diseases due to sudden climate change and over- or under-irrigation. Beyond that, it improves ventilation and irrigation schedules to achieve more yield with highest quality. Figure 9 shows the data analytics function of our digital twin software. Although our digital twin implementation operates on a fog computing-oriented sys-

Fig. 7 Monitor function of developed digital twin software

Fig. 8 Control function of developed digital twin software

tem model, it is available to performing big data analytics on historical logs when it is possible to establish a stable Internet connection with the cloud server. Through the use of powerful tools like machine learning, the cloud extension allows receiving predictive alerts and customized notifications regarding potential risks that could affect the crop yield. It also helps to proactively reduce unexpected issues.

Fig. 9 Data analytics function of developed digital twin software

5 Conclusion

In this study, we have introduced a new perspective on the smart greenhouse management system by applying the fog-connected digital twin technology. We have also presented a bidirectional communication infrastructure based on WSAN application. The proposed fog-connected digital twin approach significantly reduces the need for cloud connectivity through a secure, reliable, and high-speed network. Considering the infrastructure-constrained environments like agriculture, the fog computing can be very useful to realize the near real-time monitoring, data-driven decision-making, and data analytics functions. Although future insights have been provided with statistical methods over a short period of simulation time, the proposed system allows extending it for cloud computing to use machine learning on historical data logs. In our future work, we plan to create a cooperative platform that allows task sharing between the applications on fog and cloud layers.

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Digital Twin Applications for Smart and Connected Cities

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1 Introduction

Cities are living systems that have many subsystems such as energy management, transportation, healthcare, waste management, communication, security, food/water and education subsystems together with the people living in them. Increasing development of computerized high technology and information/communication systems enable the citizens to reach the contemporary outputs of these subsystems in a better

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_6

way. However, it comes with the need to manage all these systems harmoniously. To manage all systems coordinated, smart cities are new solutions to cope with city problems, including accommodation, vehicle traffic, air pollution, energy demand, security, food/water management, and municipal/hazardous waste treatment.

With the outstanding development of computerized technologies and electronic devices, management strategies are changing toward using sensor-supported smart systems, enabling low-cost, highly efficient solutions for the entire city. The smart city idea is generated through the need for fast and effective resource management to solve problems arising from the modern life of crowded cities, using high technology. The idea of transforming the cities into living self-managed organisms with live data-supporting sensors may also improve competitiveness while providing new alternatives for the solution of the problems related to the cities. Smart cities can be imagined as groups of intelligent subsystems communicating while sharing data related to people and other objects [1].

With the use of Information and Communications Technologies (ICT), smart cities are becoming more efficient and sustainable. The intensive use of these technologies helps cities integrate the physical and social aspects of city life. By integrating advanced monitoring and control applications, cities can maintain a higher quality of life and sustainability. There are some specific challenges that cities need to tackle in order to achieve their full potential [2]. The benefits of a smart city are limitless, and growth should accelerate in the coming years. The Internet of Things (IoT) will transform multiple industries in the near future. Collecting and using data from connected objects and machines are essential to building a smart city. By integrating data from smart devices with smart infrastructure, cities can improve their traffic flow, increase pedestrian safety, and reduce energy costs. By pairing devices and data, communities can also improve the distribution of energy and encourage alternative transportation [3].

Smart cities also provide citizens with greater safety. They can provide information on high-crime areas, improve transportation, and prevent disasters. Smart buildings can also monitor the structural health of buildings and determine when repairs are necessary. Smart technology can help to improve the efficiency of urban farming and manufacturing. Smart cities can connect all services to ensure citizens' quality of life [4]. In concept, digital cities are defined as the virtual image of cities; cyber cities are defined as governance and control; smart cities are defined as sensors, smart devices, and smartphones; and finally, intelligent cities are defined as intelligent invention ecosystems, web-based communal intelligence, and Artificial Intelligence (AI). The layers are defined to be layers 1, 2, and 3 as physical, institutional, and digital spaces, respectively. Harmonization, extension, and instrumentation intelligence show alternative ways for spatial intelligence to create effective cities. All the harmonization of the architectures of intelligence types is integrated by various types of coordination among humans, institutions, and digital systems [5].

Although there are different definitions of DT, which cause complexity about DT's eminent characteristics and differences from the casual models and simulations [6], a common definition generally used of DT is the definition that is made by NASA "A Digital Twin is an integrated multi-physics, multi-scale, probabilistic simulation of a complex product that uses the best available physical model, a real-time sensor data, historical data, etc. to mirror the life of its twin" [7, 8]. Despite the modeling and simulation being considered together in DT, there is a need to integrate these two components in order to fill in the necessary gap between them while developing the DT [7].

DT technology is the creation of a virtual representation of any object, device, or service in a digital environment. With smart sensors or IoT sensors, live, and continuous data from the physical environment is transferred as an input to the DT. The DT processes and analyzes this data and gives us output information that provides possible results that are seen in a very short time without any cost. Accordingly, any problem that may occur before starting the real activity or production can be detected and solved. Since 2014, the DT is utilized for every branch of the industry, including simulation, optimization, and decision support systems connected with IoT, AI, and cloud computing [9].

The benefits of using DT can be applied to different industries, including industry 4.0, smart city management, healthcare, manufacturing, aeronautical industry, energy management, etc. The application of DT to smart city technologies facilitates continuous improvement in the effectiveness of areas of applications in city life and the costs that are related to them. However, it can still be considered to be in the early phases of using DT in city applications since there are still problems in the sharing data safety, including the privacy of life. The developments in cyber security technologies, communication, computing, and IoT encourage, facilitate and foster the applicability of DT [10]. Additionally, DT modeling may differ according to the different levels of integration of the DT concepts [9]. A representation of the components of the DT for smart cities is stated in Fig. 1, including the environment in which the system is in.

In Sect. 2, the fundamental definitions, concepts of city planning, and smart city applications are discussed. The integration of digital technologies and their effects on daily life in city planning are explained. Additionally, the use of DT in city planning is broadly investigated. The benefits of using digital technologies that ease life in the smart city concept and the integration of DT applications for improving public transportation functions are discussed in Sect. 3. In Sect. 4, energy management and the use of DT in energy management in smart cities are explained. The use of DT in public healthcare and waste management in smart cities are discussed in Sect. 5 and Sect. 6, respectively. In Sect. 7, DT aspects in sustainable food/water security are discussed. In Sect. 8, one of the critical challenges of digital technologies, cyber security, and communication is outlined and investigated in communication technologies and cyber security in smart cities, respectively. Finally, the discussion of future work and outlook on the subjects covered in the chapter is presented in Sect. 9, and the summary of different DT future directions, identified challenges, and the conclusion are stated in Sect. 10.

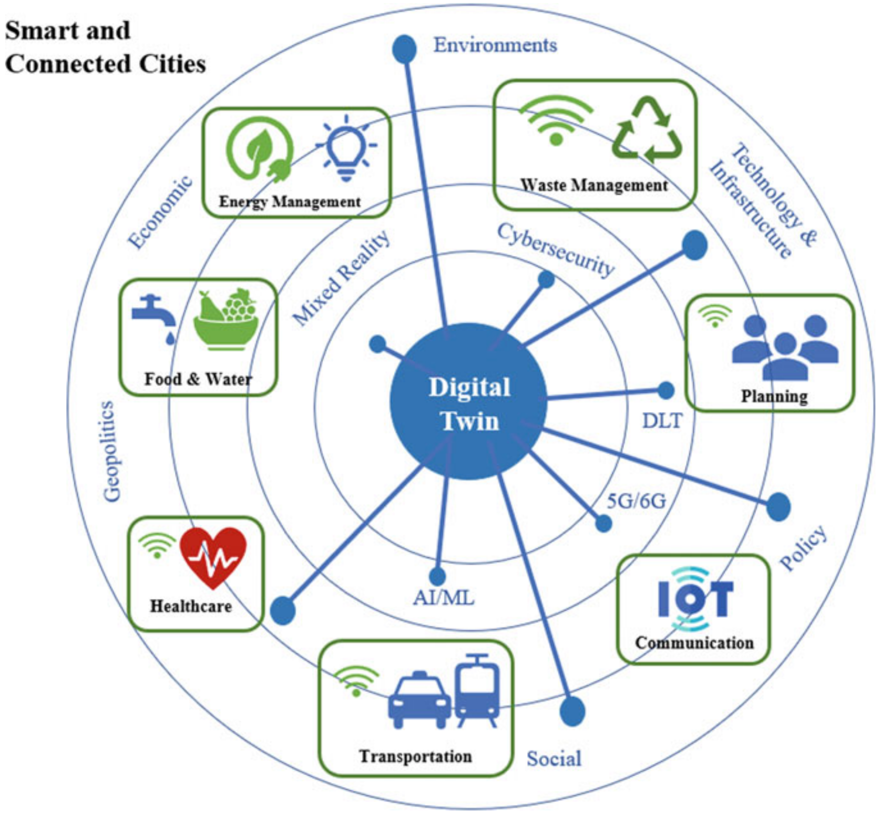

Fig. 1 Components of digital twins for smart and connected cities

2 Digital Twin for City Planning

The industrial revolution made the people start to leave agriculture and animal husbandry and migrate from villages to cities which caused the development of the smart city structure. With the increasing number of developing high-tech sensors, cities are becoming smarter. The location/activity sensor technologies and location-based services create location-based big data [11].

DTs were first intended to evolve the processes related to manufacturing with the help of simulations that enable the managers to understand the system's behavior and obtain sensitive models of designed/actual components. Nevertheless, with the increasing development and eminence of accurate sensor-supported information systems with big data obtained from IoT systems in smart cities, it becomes real to generate DT smart cities. In this way, 3D city models can be disclosed to the citizens and be updated interactively according to the feedback of public opinion [12]. With the help of legislative rules, citizens can also provide input to all city-based problems, including solution alternatives that can be implemented to solve them. The rapid reaction can be commenced by immediately testing these alternatives with the existing ones via DT technologies.

DT has the opportunity to convert the data-driven virtual infrastructure to real-life infrastructure in order to satisfy everyday life. That is possible by managing to transform potential infrastructure resources into cyber-physical systems [13]. The DT enables the decision-makers to track the cities' real-time behavior and helps to carry out more effective control [14]. However, it has been detected that numerous smart city perspectives fail to organize the bottom-level interactions that are far from satisfying the local needs of their province while taking into account the necessary privacy and security rules.

The smart city concept should be studied in a multidisciplinary way of looking. That is, the area of interest related to the applications of smart cities includes not only architecture, urban planning, and public transportation but also the other disciplines, including the social sciences like the economy, psychology, sociology, geography, and engineering sciences like computer sciences, energy, electrical, mechanical, and civil engineering. On the other hand, there arouses to synchronize all the activities and interactions between these disciplines. In order to coordinately make every of the infrastructure physical systems more efficient and effective, there is a need to keep track of the data related to them and update them accordingly. It is possible to achieve all via the use of DT. The role of digital technologies is to make the subsystems interconnected, instrumented, and intelligent in the cities. The interconnection is achieved by joining and communicating different components [5]. In a DT smart city, there may be several layers of information: terrain, buildings, infrastructure, transportation, digital layer, and virtual layer. The data collection is achieved by the smart city digital layer, and the collected data are used by the DT virtual layer. Accordingly, the DT performs optimization procedures related to mobility, energy, city planning, etc. [12].

3 Digital Twin for Public Transportation

With the development of smart city technologies and applications, smart transportation, which is one of the components of smart city infrastructures, become a tempting interest for city management [15]. Starting from 1980 till now, smart public transportation has evolved continuously with the worldwide concept of cooperative intelligent public transport systems (C-ITS) in Smart Cities The related technologies for the application of C-ITS are 5G and 6G techno systems, big data, cloud computing, AI, and analysis engine, IoT, Autonomous Vehicles (AV), Connected and Autonomous Vehicles (CAV), DT, Building Information Modeling (BIM), the electric bus, hydrogen fuel cells, cybersecurity, Geographic Information System (GIS) spatial analysis, and global standardization, recommendation, and specifications for C-ITS [16].

A DT may also improve transportation and travel systems in general. Together with public transportation, hazardous and non-hazardous materials supply chains also need transportation and make the transportation systems more complex, including oil and Liquefied Natural Gas (LNG) transportation [17, 18]. Creating DT of road infrastructure greatly aids asset management operations as well as enables new construction materials projects to be more efficient than ever before and get rid of even more complex traffic problems. It has the potential to save money and reduce emissions on all road networks.

DT technology is an innovative technology that has a lot of knowledge about vehicle and road development, operation, infrastructure maintenance, and traffic data. Due to the increasing population, the traffic is constantly getting crowded, the infrastructure is getting insufficient, causing traffic jams. Transport and transport infrastructure is one of the most fundamental building blocks in the construction of smart cities [19]. With DT, it is possible to find effective solutions to traffic getting crowded daily. Via DT technologies, it becomes possible to get rid of problems in city traffic harmoniously. Additionally, we can manage road network traffic effectively and in a contemporary way with smart and innovative transportation systems. With smart traffic monitoring methods, information transfer between vehicles and roads may be possible. These efforts can reduce traffic, increase road network capacity, mitigate accidents, save energy, and lower pollution.

When implementing DT technology, all the components and the environment need to actively communicate with each other on models. These technologies include wireless communication technology. This enables more efficient, safer, and smarter communication will take place much faster than before. Coordinated modeling with 4G, 5G, and more advanced technologies enables real-time transmission of digital twins [20].

4 Digital Twin for Energy Management

One of the most important things in smart cities is the optimal management of its resources, especially more efficient energy management related to five main intervention areas: generation, storage, infrastructure, facilities, and transport [21]. Adequate representation of urban dynamics in a DT of all five intervention areas can lead in the future to a more thorough better analysis of possible energy-policy alternatives even before the changes in the city management are implemented. According to Calvillo [21], generation provides energy, storage provides availability, and infrastructure distributes the energy and interfaces for users, with the facilities and transport (mobility) as the final component of energy intervention areas. All these five main energy smart city components provide main layers: intelligence (control/management), communication, and hardware (physical elements and devices) [21]. The next generation energy management systems are expected to utilize AI, Distributed Ledger Technology (DLT), and other advanced ICT in an interconnected and inter-operable manner with DT infrastructure.

5 Digital Twin for Public Healthcare

Public healthcare seeks to improve the health of communities through the prevention and treatment of diseases and promoting wellness with a healthy lifestyle, such as exercise and healthy eating habits. One of the critical missions of public health is to prevent people from getting sick, while personalized health focuses on the diagnosis of diseases.

Protecting and improving the health of people and their communities become more significant with the COVID-19 pandemic [22]. It taught us the importance of public healthcare data to run data analytics and implement complex city-wide precautions. Lessons learned from this pandemic, and technological advancement have the potential to accelerate the digital twin use for more digital and inclusive smart cities [23].

With the increased population of cities, the urban population represents almost 60% of the world's population [24]. The urban population generates a vast amount of data using diverse smart devices, including smartphones, watches, and apps used smart devices. Incorporating these individual data to form a digital twin for public healthcare in smart cities will provide enormous potential. The well-being of the individual depends on the health and contentment of the community that they are living with. That's why data-driven models for public safety and health could enhance lives in a smart city. The digital twin concept plays an important role to sustain connected and proactive healthcare. Public health professionals should analyze and interpret divergent factors to understand and determine public health issues to achieve this goal. DT in smart cities will enhance public health through data-driven insights.

Public health-related processes will be organized, monitored, and assessed more effectively with the adoption of DT in smart cities. Despite human DTs, DT use in public health could be adopted sooner since its benefit could be observed by infection tracking and containment. The management of public issues such as vaccination, screening, and social distancing could be arranged effectively. These population-level digital twin systems will enhance digital public health by means of data-driven models. To fight future pandemics, patients' health and historical medical data will be fully utilized with the help of artificial intelligence [25]. DT in smart cities could also transform the communities to sustain healthier lifestyles.

A real-time and data-driven DT for public healthcare can avert health crises even before it forms by predictive analysis. DT allows integrated and inter-operable public healthcare and better use of limited healthcare resources with the help of real-time IoT sensor data.

6 Digital Twin for Waste Management

Waste management is achieved by systematically implementing subsequent procedures. These procedures comprise the preventing and decreasing the waste generation, collection, classification, accumulation, storage, transporting, recycling and recovery, disposal of wastes, and checking/supervising the wastes. Waste minimization also aims to minimize the costs and risks related to generated wastes [26].

Waste management in a city may include the minimization of domestic, medical, hazardous, and non-hazardous wastes, separation of the wastes while collecting at the source, intermediate storage, the installation of transfer facilities, transportation, recovery, disposal, operating the recovery, and disposal centers, closure, after-closure maintenance.

The IoT offers new alternative solutions to create smart cities. With the IoT, smart parking guidance systems direct cars to free parking spaces, or systems can be developed that can help reduce gas emissions. Intelligent and flexible approaches provide a basis for such technologies. The next generation of waste management and recycling systems is also a result of this approach. Using a combination of data and machine learning, our technology creates a digital twin or virtual copy of the waste environment in cities. This forms the basis of optimizing the process. If we look at the DT issue in waste management in general, we can see that it is very comprehensive. The DT technologies created can show us many good aspects that are brought to nature by reproducing with more affordable, low-cost waste management materials. For smart waste management in the cities, both private waste management companies and municipalities can benefit from smart waste management technologies. With the cheaper sensors and increased prevalence, all waste management services can manage waste in cities with operational efficiency and at less cost. With the adoption of Industry 4.0, wireless technologies developed to make our business efficient and smarter are becoming more common, and their costs are decreasing. These technologies, which offer us the opportunity to produce unlimited innovative ideas, are easily applicable for controlling, recycling, and protecting our health [27].

The world population and consumption are increasing at an unprecedented rate. The increasing rate of this consumption creates tremendous waste that is serious for the survival of the world and the living. Around 2.12 billion tons of waste, mostly plastic, are produced in the world every year, and these wastes cause great harm to nature. With DT. It becomes possible to create an eco-friendly economy model based on the principle of recycling waste. Via DT technologies, as public awareness of waste increases, it becomes possible to have rapid alternative constructive solutions to the climate crisis and environmental problems, By using DT and cloud-based technologies, it is possible to make waste collection applications. Accordingly, the residents can dispose of the garbage using the recycling bins in every neighborhood by the generated rules. It becomes possible to track where the product is and in what period it can be recycled by scanning the QR codes placed in those containers and the QR code placed in the product that is discarded via smart devices [28]. By using DT, it becomes possible to manage waste generation, collection and recycling, and recovery by checking the processes of reducing waste, separating them according to categories, collecting them according to categories, recycling wastes, and recycling wastes with and evaluated data.

Using IoT technologies, many innovative applications can be developed, such as storing food at a demand-in-demand rate in grocery stores, preventing spoilage by monitoring food, or identifying waste that can be recycled. With intelligent waste management systems, the desired level of efficiency can be achieved with smarter and more robust decisions, unlike traditional waste management systems [29].

The digital twin concept is already being used by city planners to help them create environment-friendly buildings and minimize energy costs. By using the DT concept for waste management in smart cities, city planners can evolve more quickly and efficiently in response to events or the seemingly mundane daily life of traffic jams. The development of the smart city DT for waste management is supported by the intersection of smart city DT capabilities and disaster management needs. By implementing smart city DT technology to this specific need, it is possible to decrease these risks while accomplishing a better quality of life [30].

7 Digital Twin for Sustainable Food and Water Security

Access to healthy and affordable food, as a fundamental individual right, is one of the most important challenges in urban communities [31]. Beside security of food, it is also very critical to sustain the water needs of the residential areas including smart cities. [32] Utilizing Smart technologies, IoT, and data analytics techniques for addressing food insecurity is not a straightforward task because of their structural differences, and it requires careful consideration of various factors [33]. The food system consists of five main divisions: production, processing, distribution and transportation, marketing, and consumption [34]. Considering these various actors in the food system, there is no single solution to address food insecurity. Therefore, to better address food insecurity and increase transparency, there is a need to connect different areas in this system through the use of data, automation, model-based techniques, and smart technologies. Emerging digitalization technologies helps to provide secure and healthy water resources to satisfy the needs of the residents of future smart and connected communities. Smart cities solutions can be used to address food and water insecurity in different fields.

- Develop a model-based approach to analyze the food system as a dynamic system with a set of inputs and outputs [33],
- Data collection, real-time situation monitoring, and usage of data analytics techniques in both supply side and demand side,
- Controlled environment agriculture CPS [35] and smart farming [36],
- AI, machine learning, and IoT devices in food distribution and delivery (for example, for improving food traceability and safety in the food supply chain) [37],
- The use of emerging technology innovation for energy management (for example, the use of renewable energy sources) [38],
- The use of smart technologies and IoT-based devices for food waste reduction and management [39],
- Deployment of state-of-the-art smart water and irrigation techniques has a potential to reduce the impacts of climate change and increase the life quality of the residents in a society [40],

- DT technology has a considerable potential by offering new opportunities to create healthier societies supplied by sustainable food and water resources. Digital twining of municipal water supply system or agricultural processes can be counted as promising fields in this category.

8 Communication and Cybersecurity Aspects

With communication and computing technologies along with the Internet of Things (IoT), the implementation of DT has become more popular in many industries due to its cost-effectiveness, feasibility, and ease of use [41, 42]. The smart city concept may be one of the best examples, which is a very complicated and sensitive system in terms of architecture (physical and digital). DT allow the simulation of plans before implementing any subsystem in the smart city, i.e., power grid, water grid, transportation, etc., exposing problems before they become a reality. Communication and cybersecurity are two main digital components for architectural aspects that could be planned and analyzed in a smart city system [43]. It is required to evaluate the system performance in terms of communication capabilities as well as the vulnerability in terms of cyber threats.

Various sensors communicate with the digital twin. DT will be in communication with each other in the near future. We should also note that such implementations use several technologies that have different vulnerabilities. These systems are open to several attack vectors in different implementation layers. The threats and some (but not all) countermeasures are shown in Table 1 and summarized in [44]. Most threats are related to cybersecurity attacks rather than physical threats, such as data modification, software, data communication, system, data securing, and machine learning threats. Model learning attack, among them, is a new type of attack, i.e., model poisoning, which aims to reduce the model's performance by uploading "poisoned" updates. Fortunately, potential countermeasures are available to deal with each type

Table 1 Digital twin threats and countermeasures [44]

Threats	Countermeasures
Physical threats	Physical security
System threats	Firewall, IDS, access control, antiwalware, system hardening
Software threats	Secure SDLC, software hardening, security testing
Machine learning threats	Data sanitization, security assessment mechanisms, privacy preserving techniques, algorithm robustness enhancement
Data modification threats	Hash, IPFS, blockchain, tamper-proof and tamper-resistant hardware
Data communication threats	Cryptographic solutions, firewall, IDS, network resiliency, blockchain
Data storing threats	Cryptographic solutions

of attack. They have been widely used for increasing security in all communication layers, especially against system threats, in the industry. It is obvious that they will be used to increase safety and security in smart cities for systems and citizens.

9 Discussion and Observation

The digital twin has become popular for smart cities along with advanced communication, computing, and cybersecurity technologies in recent years. These technologies make it easy to implement smart cities through DT. The smart city systems, from the power grid to transportation, can be evaluated in terms of performance, i.e., operation, communication, computing as well as security, in a simulated environment with digital twins. This allows the investigation of any issues before happening. It is very crucial for smart cities to have very sensitive applications for citizens. Overall, it is obvious that the importance of DTs has been increasing for smart cities along with benefits and challenges as follows:

Observation 1: DT can significantly improve citizen life standards in smart cities.

Observation 2: DT can reduce the vulnerabilities of smart city applications in terms of safety and security by exposing problems before they become a reality.

Observation 3: DT will provide more information to the city operators as well as citizens to share the resources more efficiently and effectively.

Observation 4: DT will enable smart city application planning, management, and optimization.

Observation 5: DT will allow planners to examine how new smart city applications fit into existing cities and their impact.

Observation 6: DT will allow city planners to apply environmental solutions to manage municipal problems.

10 Summary

In recent years, DTs have been playing a critical tool in realizing smarter cities and location is essential to DT. Smart cities are complex systems, including several subsystems that need to continuously control and operate properly for citizens. Also, they are constantly evolving so their corresponding DTs have to be constantly updated. These subsystems are public transportation, communication, waste management, and energy management to public healthcare. The main benefit of having up to date information in the form of DT is providing an environment to simulate the smart city to evaluate the smart city applications in terms of productivity, efficiency, availability, safety, and vulnerability. This chapter explained how we can implement DT technologies in smart city applications along with the fundamental definitions, concepts of city planning, and smart city applications. In addition, it provided a brief review of the critical challenges of the use of digital technologies in terms of cybersecurity and communication.

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Digital Twin in Industry 4.0 and Beyond Applications

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1 Introduction

The digital twin concept was first introduced by Dr. Michael Grieves, who presented the idea that the physical system should be mirrored by its virtual equivalent [1–4]. The virtual model nowadays known as digital twin (DT) can be used as the base for decision-making that might mitigate multiple problematic issues that are happening

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_7

if the various parts of the enterprise are using different data for the same system [2]. The main notion of the concept of the digital twin is centralizing the data that can be used by various stakeholders for a better understanding of system behavior [3]. The virtual model should represent the real model and, in such form, may serve as the vehicle through which we could understand all different phases in the product lifecycle management. Breaking the barriers between different departments can help companies to break down the barriers that exist among the different silos in the separate design and manufacturing departments in different companies. A more streamlined decision-making process can be obtained if the same virtual model (digital twin) would be linked to all the data that is being used in all different engineering processes and disciplines [4]. Digital twin methodologies have resided in the push from companies doing business in global collaborative environments to have one central source of data that can be shared among the various company functions and engineering ones but also the parts of the company that does not necessarily have licences for the all necessary software to access the engineering related data. One of the main issues related to accessing the most current and up to date data which is companies is related to usage of offline files, not having enough licenses for all different software that is used at various jobs, different security upgrades, cyberercuirty firewall issues, and different organization role data base management access rights.

A digital twin technology provides us the ability to transform a real system/model into its virtual imitation [5]. Additionally, Industry 4.0 has changed the manufacturing, management, and logistics industries by adding new technologies that effectively use different industrial procedures and decrease costs and necessary workforce/machinery. DT technology has become a remedy due to the rapid improvement of technology demand in Industry 4.0, which aims to provide an interactive liaison between a physical system and the imitated models of its live or near real-time interchange of data between them. This capability fosters the manufacturers to satisfy the demand trend of the customers. On the other hand, use of digital twin technology is increasing the work that has to be done in relation to data base backup, user rights management, online storage space, cybersecurity issues, and constant changes in the roles who has access to which data, migration issues when new software is being introduced, costs related to the software licensing, etc.

Section 2 discusses the concept of understanding the digital twin in Industry 4.0 and beyond applications. The main aspects of the emergence of digital technologies in daily life are discussed in this chapter. In addition, such emerging technologies are driving various industries to change the ways they run their product design, production, maintenance, and operating procedures, but also the end of the lifecycle, recycling, and disposal operations. In Sect. 3, the topic is investigated within the facility management domain. The digital twin is also integrated into the operating procedures of physical assets that are explained with their virtual counterparts. Then, the digital twin in smart cities discussion is given in Sect. 4. Digital assets in the sense of the whole network of buildings, their own utilities, HVAC systems, water distribution systems, and all other mechanical and electrical systems are part of the modern building and facility operation. In Sect. 5, the discussion about different digital twin facets is presented. Finally, the conclusion will be given in Sect. 6, which summarizes various digital twin future directions and challenges.

2 Digitalization and Industry 4.0

Digital technologies are slowly but surely becoming a norm in daily life. Many traditional ways of doing things, such as monetary exchange, have seen completely new ways of shifting people to use different models [6]. Digitalization of various industrial verticals such as energy, healthcare, smart cities, manufacturing, transportation, and supply chain inevitably triggers massive and fundamental changes in society [7]. Artificial intelligence (AI), distributed ledger technology (DLT), cloud computing, 5G, robotics, and Internet of things (IoT) are among the most promising enabler of Industry 4.0 technologies. Extended reality (XR), as an overarching technology framework that accommodates augmented reality (AR), virtual reality (VR), and mixed reality (MR), plays an interface and gateway role between the real and the DT worlds (Fig. 1).

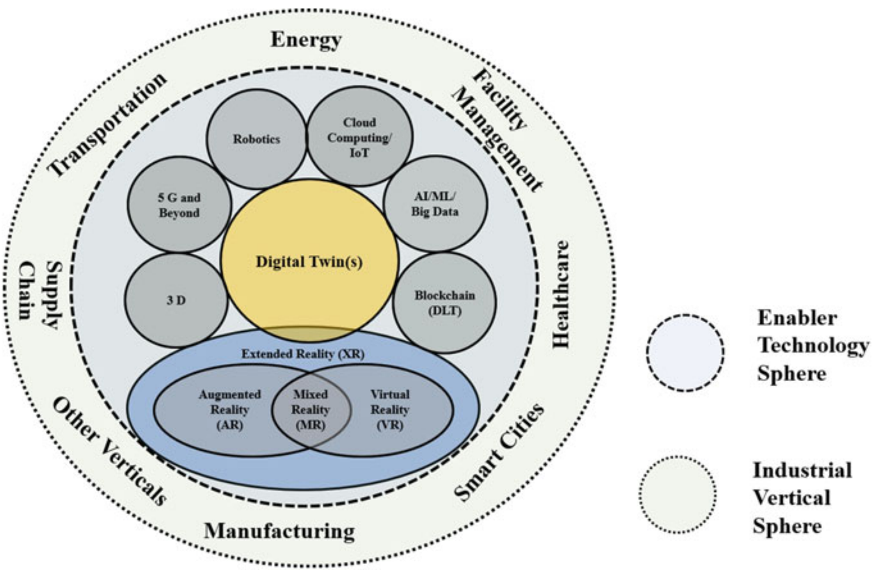

Fig. 1 Enabler technologies and industrial vertical spheres on digital twin

3 Industry 4.0 Technologies

Industrial 4.0 is the transformation from the traditional to the modern production along with advanced communication, cloud computing, automation technologies, the Internet of things (IoT), and cyber-physical systems.

3.1 Artificial Intelligence

The concept of digital twins can be used in various industrial applications such as transportation, healthcare, manufacturing, retail, and many other applications [8]. Digital twins are often used in the Industry 4.0 domain to demonstrate the relationship between the physical and virtual world. This virtual world can be used to monitor, predict, and optimize the performance of the physical world along with artificial intelligence (AI) methods. Some of the well-known AI applications of digital twins are as follows:

- Intelligent agents
- Predictive maintenance
- Product lifecycle management
- Personalized healthcare
- Intelligent transportation systems
- Smart buildings
- Smart grids

Various AI algorithms can be used to train digital twins to simulate the physical world more accurately. These algorithms learn the behavior of the physical world and then understand the complex patterns in the data. Various reinforcement learning algorithms can also be used to train the digital twins to take action in the physical world and to learn the optimal actions that need to be taken in the physical world.

3.2 Internet of Things (IoT)

The Internet of things (IoT) technology using Internet data communications concepts has become more popular with widely use of intelligent inputs and outputs (analog, digital, video, audio) in almost every field, such as energy, healthcare, transportation, vehicle safety, agriculture, manufacturing, and many more. The IoT uses modern wireless telecommunications technologies (e.g., Wi-Fi, NB-IoT, LoRa, Sigfox, Bluetooth, Z-Wave, ZigBee, WirelessHART, and Thread) and protocols (e.g., AMQP, MQTT, CoAP, XMPP, LWM2M, and DDS) [9]. With the use of IoT technology, the other technologies such as massive sensing and control, big data, and advanced levels of optimization and efficiency have been started to used in industry. However, it also raises security concerns [10].

IoT technology is a key technology in Industry 4.0 by significantly contributing to the advanced automation and data analytics to make the manufacturing environments more efficient. It is also called the industrial Internet of things (IIoT), which is a big transformation of legacy infrastructures and processes to a smart manufacturing and process. It has a high impact on the industry along with Industry 4.0 [11]. Many industries have already started to use IoT devices inside their systems with advanced communication technologies to assist them in collecting, monitoring, and analyzing.

3.3 Distributed Ledger Technology

Distributed ledger technology (DLT) refers to a digital system that allows recording the data and transactions of assets in a distributed, secure, and immutable manner by using certain infrastructure and protocols using cryptographic functions for validation [12]. Blockchain technology is a commonly used subset of DLT. Therefore, DLT and blockchain technology might be used in an interchangeable manner. DLT is expected to play an enabler role with the full digital ecosystems, which can link the real and virtual worlds with the scope of DT use cases. DLT-based systems do not only aim to increase economic productivity by eliminating the unnecessary third parties in various Industry 4.0 use cases but also provide a certain degree of cybersecurity due to the deployed validation mechanisms and the encryption methods behind them [13].

DLT is considered to be a very fruitful enabler technology for various industrial verticals such as energy, heath-care, logistics, transportation, and many other domains. Peer-to-peer energy trading, electric vehicle charging, renewable energy certificate trading, and energy finance use cases are the most promising implementations [14]. Logistic and supply chain are an other high potential application areas where DLT can be used to track record the route and origin of the commodities transferred. Joint use of DLT and DT offers various undiscovered play ground for the next generation Industry 4.0 applications.

3.4 Cyber-Physical Systems (CPS)

Cyber-physical systems (CPS) are smart systems composed of networked hardware and software components integrated with physical elements through sensing and actuation [15]. CPS and digital twin are two fundamental elements for Industry 4.0 to achieve fully industrial automation and smart manufacturing through model-based design, distributed control, real-time management, virtualization, AI, and environmental learning and predictions [16, 17]. While CPS and DT are not the same in many perspectives, the successful integration of them would enhance resiliency, efficiency, intelligence, transparency, and feasibility of functions in smart manufacturing systems [18].

Recent studies suggest the extended version of CPS by adding the social space and sciences to the existing convention. The extended emerging framework is named cyber-physical-social systems (CPSS). Cali et al. in [19] presented multi-layer CPSS framework for the energy domain where physical space represented the power systems, cyber space represented ICT, and data analytics-related work, and social space involves power market, energy policy, and other social science-related aspects. CPS and CPSS approaches are quite handy for DT frameworks since such work combines cyber, physical, and in some cases social domains together in a holistic way.

3.5 Cybersecurity

Industry 4.0 introduces new cybersecurity threats that did not exist in earlier industrial revolutions. The main cybersecurity threat actors in Industry 4.0 are as follows:

- **Hackers**: Hackers are individuals or groups who break into computer systems for malicious or criminal purposes. They can steal data, damage systems, or disrupt operations.
- **Cyber criminals**: Cyber criminals are individuals or groups who use computer networks to commit crimes such as fraud, extortion, and identity theft.
- **State-sponsored hackers**: State-sponsored hackers are individuals or groups sponsored or supported by a state or government to conduct cyberattacks against other countries or organizations.
- **Terrorists**: Terrorists are individuals or groups who use computer networks to spread fear and terrorize people. They can use cyberattacks to damage infrastructure or steal data.
- **Organized crime groups**: Organized crime groups are groups of criminals who cooperate to commit crimes such as fraud, extortion, and intellectual property theft. They often use computer networks to facilitate their activities.
- **Hacktivists**: Hacktivists are individuals or groups who use computer networks to promote a political or social agenda by breaking into systems and stealing or damaging data.
- **Cyber spies**: Cyber spies are individuals or groups who use computer networks to steal sensitive information from governments, businesses, or individuals.

Industry 4.0's cybersecurity threats Industry 4.0 is susceptible to a variety of cybersecurity threats, including:

- **Malware**: Malware is a broad term used to describe a variety of malicious software, including viruses, worms, and Trojan horses. Malware can damage or disable equipment, steal or corrupt data, or interfere with the operation of industrial control systems.
- **Phishing**: Phishing is a type of social engineering attack in which an attacker sends fraudulent emails or text messages in an attempt to steal sensitive information, such

as login credentials or credit card numbers. Phishing attacks can be hazardous in industrial environments, where they can be used to exploit vulnerabilities in industrial control systems.
- **Insider threats**: Insider threats are a severe concern in industrial environments, where disgruntled or careless employees can easily exploit vulnerabilities in industrial control systems.
- **DDoS attacks**: DDoS attacks are a type of attack in which an attacker floods a target system with traffic or requests, overwhelming its capacity, and preventing legitimate users from accessing the system. DDoS attacks can be hazardous in industrial environments, where they can be used to disrupt the operation of critical systems.
- **Network attacks**: Network attacks are a type of attack in which an attacker attempts to gain access to or disrupt the operation of a network. Network attacks can be hazardous in industrial environments, where they can be used to gain access to sensitive data or disrupt the process of critical systems.
- **Physical security threats**: Physical security threats are a severe concern in industrial environments, where unauthorized access to critical systems can result in severe damage or loss of life. Physical security threats can include everything from vandalism to theft to sabotage.
- **Cybersecurity vulnerabilities**: Cybersecurity vulnerabilities are weaknesses in industrial control systems that attackers can exploit. Cybersecurity vulnerabilities can be introduced through faulty design, insecure coding practices, or poor password management.
- **Rogue employees**: Rogue employees are employees who have been compromised by attackers and are now working for the benefit of the attackers rather than the company. Rogue employees can pose a serious threat to industrial control systems, as they may have access to sensitive data or systems and may be able to exploit vulnerabilities in those systems.
- **Social engineering attacks**: Social engineering attacks are attacks in which an attacker uses deception to gain access to sensitive information or systems. Social engineering attacks can be hazardous in industrial environments, where they can be used to exploit vulnerabilities in industrial control systems.
- **Third-party risks**: They are the risks associated with third-party vendors' use in industrial environments. Third-party vendors may have access to sensitive data or systems and may be susceptible to cyberattacks. As a result, it is essential to carefully vet any third-party vendors used in industrial environments.

The current state of cybersecurity in Industry 4.0 is a cause for concern. Many industrial control systems are vulnerable to various cyberattacks, and the number of attacks is increasing every year. As a result, it is essential to take steps to secure industrial control systems against cyberattacks. Some steps that can be taken to improve cybersecurity in Industry 4.0 include as follows:

- **Implementing strong security controls**: Strong security controls, such as firewalls, intrusion detection systems, and antivirus software, can help protect industrial control systems from cyberattacks.

- **Educating employees**: Employees need to be aware of the dangers posed by cyberattacks and the steps that can be taken to protect themselves and the organization. Employees should be trained to identify phishing attacks, protect their login credentials, and report suspicious activity.
- **Patching vulnerabilities**: Vulnerabilities in industrial control systems can be exploited by attackers, so it is important to patch these vulnerabilities as soon as they are discovered.
- **Using solid passwords**: Strong passwords can help to protect industrial control systems from unauthorized access. Passwords should be changed regularly and should not be shared with anyone.
- **Conducting risk assessments**: Risk assessments can help organizations identify the most likely vulnerabilities to be exploited by attackers and take steps to mitigate those risks.
- **Implementing security awareness programs**: Security awareness programs can help employees to understand the dangers posed by cyberattacks and how to protect themselves and the organization.
- **Using security tools**: Security tools, such as firewalls, intrusion detection systems, and antivirus software, can help to protect industrial control systems from cyberattacks.
- **Developing incident response plans**: Incident response plans can help organizations respond quickly and effectively to any cyberattacks.
- **Conducting risk assessments**: Risk assessments can help organizations identify the vulnerabilities that are most likely to be exploited by attackers and take steps to mitigate those risks.
- **Monitoring network activity**: Network activity can be monitored to help identify any suspicious or unauthorized activity.

3.6 5G and Beyond

Communication technologies have been a key driver all the time in humanity. However, it is the devices' age along with Industry 4.0, not the people. In future, more billion devices will be able to connect to each other for various purposes in the Industry 4.0 environment. The question is how do billions of devices connect at a time? It is needed advanced communication technologies to meet the requirements for each application. The answer is "next generation communication networks: 5G and beyond". With the commercialization of fifth-generation (5G) technology, the communications industry has been more visible and used in almost all areas. Especially, 5G networks can provide many new capabilities, features, and advantages to operate services and applications for the industry. For example, the automation application is widely used in many sectors, from electric and gas utilities, factories, warehouses, and farms to many others, which needs real-time or near real-time communication to monitor and control many devices at a time as well as to operate the business properly. 5G networks are one of the main actors in Industries 4.0 and beyond, which provides an all-in-one communication platform along with new business models and better capabilities than existing communication technologies [20]. With the use of 5G networks in Industry 4.0, the digital twin provides a digital profile, which represents the historical and current behavior of a physical object to improve process and business performance. Companies can create physical issues in the digital environment, predict outcomes more accurately, and build better products through the digital twin. They can also create a footprint for products from design and development to the end of the product lifecycle in a digital environment. This helps them understand the product, improve their operations, reduce defects, and emerging new business models to drive revenue using next generation communication technologies, i.e., 5G and beyond [21].

3.7 Robotics and Autonomous Driving

One of the applications of digital twins in robotics is mapping the physical world so that the 3D data points can be used as reference points for easier robotic navigation through the physical environment [22]. Important environmental data points can be pre-scanned or designed in the parametric model space and serve as a data set for collision avoidance path planning. For that purpose, the 3D laser can be integrated with different vision or distance sensors and provide triangulation methods for the robotic device to gather important information related to its environment. Also, robotic systems can have an integrated 3D laser range finder that can create a point cloud that can then be compared with predefined coordinate systems and important locations so that robot can be readjusted to the environment [22]. These volumetric models can include data from various scanners and provide 2D or 3D data that can be further digitized and used for robot navigation. However, 3D range processing will also lead to the need for higher processing power, faster data processing, and also further challenges in data retrieval, storage, and analysis. For this purpose, further developments in different data science and AI methods are needed so that optimization problems can be solved in real-time and that data can be used when needed for robotic navigation. Real-time data can further be used for dynamic collision avoidance, usually comprised of five steps: data acquisition, registration, planning, robot control, iteration, and integration [22]. At the same time, digital twin technology is also being used to plan robot trajectories in the virtual simulation environment. Also, the robots that are now working with workers in the same manufacturing cells (cobots) can also create their digital twin virtual replica so that the physical robot can be programmed in a more reliable way with less interactions and trial and error experiments during their setup [23].

3.8 Additive Manufacturing

Digital twin in additive manufacturing is used for prediction of different parameters related to the time needed, space required, and prediction of metallurgical properties of the additive manufactured component, but also to define process parameters such as solidification and cooling rates, trajectories, and determination of control programs needed for positioning and additive manufacturing equipment heating, environmental parameter regulation, and motion control [24]. Another cybersecurity-related analysis and determination of safe and secure data sharing methods have led to the application of blockchain technology in file transaction processes so that a more controlled supply chain can be created with the needed trust embedded in the data transaction and also enable trust that the correct part is installed in a specific application, by being used for component tracking and identification [25]. Another application of digital twins can be found in cloud-based and deep learning-enabled metal AM layer defect analysis [26]. Also, the digital twin can be used as a virtual replica that can have a virtual model representing complex additive manufacturing processes that can be used to predict possible flaws in components that are about to be made with one of the additive manufacturing methods that need a complex temperature, atmosphere, and motion control regulation based on the physics-based modeling, in situ sensing, and data analytics [27]. The digital twin can be used in other additive manufacturing applications for robotic arms toolpath planning and simulation [28]. Also, the digital twin can be used to determine customized components and to avoid the trial and error approach, which is often used as a strategy for programming additive manufacturing equipment [28].

4 Industry 4.0 Application Areas

The following areas will be investigated in subsections.

- Energy
- Agriculture
- Transportation
- Healthcare
- Manufacturing
- Supply chain
- Facility management
- Smart cities and connected communities

4.1 Energy

Energy is the key resource for all industries to maintain their operations. For this reason, all industries have been trying to find ways to use and consume energy more effectively. This goal will be achieved with the use of green energy resources through Industry 4.0 [29]. Industry 4.0 will also enable decentralization, with energy coming from local renewable energy resources, such as solar photovoltaic or wind systems. This will help the integration of renewable energy resources into the existing power grid and users to manage and control their energy use.

One of the most important issues is the use of many renewable resources together due to their variable or intermittent nature. This issue is solved through Industry 4.0 by enabling virtual plants consisting of distributed energy storage and generation resources, batteries, solar farms, wind farms, CHP units, etc. The operation of a virtual plant is run through a cloud-based architecture allowing monitoring and control of many IoT devices in the units. Besides the decarbonization use cases of the energy domain, DT-based solutions such as advance maintenance and remote monitoring systems which are designed to mimic the 3D environment of the energy assets such as offshore wind farms would also reduce the potential risks and hazards related to site visits where the assets are operational in risky conditions.

4.2 Agriculture

The need for the use of digital twin arouses from the discrepancy between the scope and scale of the business problems. While a number of the digital twin studies are in the manufacturing and manufacturing-related branches, the researchers faced many challenges in supporting different integration levels through different applications of smart systems. Furthermore, maintaining quality is crucial in agriculture supply chain (ASC) to satisfy the solutions to these problems. The agricultural industry tries to satisfy this demand by integrating smart technologies into ASC [30]. In [31], study the appropriate Industry 4.0 technologies and related reference architecture models to cope with the most complex digital twin included applications. The same architecture can be applied to Agriculture 4.0 applications. The three components, such as human, process, and technology, should be appropriately harmonized through a digital transformation using a digital twin, digital clone, and digital threat. Digital clone stands for humans while digital thread for processes, and digital twin resembles the technology.

Agriculture has become one of the most crucial strategic industries with the increasing population of the world and the negative effects of global warming. To ensure food security, countries are trying to increase the productivity of agricultural areas by converting traditional agricultural applications to more effective smart methodologies. The emerging trend through the use of modern and smart technologies is the use of Agriculture 4.0. The digital twin is an instrument that companies make use of it while switching traditional methodologies to modern ones. However, most of the current applications are still not cultivated in Agriculture 4.0 concept, and they are in the research/prototypical phase where 69 of them are carried out on open farms, and 31 of them are on indoor farms. The difference between conventional and modern agriculture is the use of digital technologies, including digital twin technologies, self-driving robotic systems, the Internet of things, and sensor technologies [32]. Additionally, [33] proposes a mission-oriented agricultural innovation systems (MAIS) method that may lead to designing the agricultural innovation systems for every environment that design enabling food transformation. The role of innovation systems in agriculture affects the conversion of the food supply systems. These can be classified as agroecology, digital agriculture, Agriculture 4.0, AgTech, FoodTech, and vertical agriculture.

Current conventional methods are converted to an optimized value chain via different emerging Agriculture 4.0 technologies. These technologies are classified into three groups of field states by [34]: prefield state, infield state, and post-field state. They classify all these three groups as consolidated and emerging technologies. For the prefield state, enterprise resource planning (ERP), chemistry, and nanotechnology are examples of consolidated, and agricultural Internet of things (AIoT), next generation genomics, AI, cellular agriculture, and 3D food printing are some of the examples of the emerging technologies. For infield state, geoinformatics, new hardware, software, and ERP are consolidated technologies, and cloud computing, mobile and autonomous robots, unmanned aerial vehicle (UAV), electrical agricultural machinery, and sensing technologies are some of the examples of the emerging technologies. And finally, for the last group, post-field state, radio frequency identification (RFID), information and communication technology (ICT), near field communication (NFC), and geoinformatics are examples of consolidated technologies, while blockchain, cloud computing, robotization of internal audit, traceability, and forecasting engine are the examples of the emerging technologies.

Despite some advantages of the digitalization of agriculture, there are also discussions about the difficulties, accordingly [35]. There is a need to guarantee the increase of food production unless suffering any opposite societal responses. The trade-off between digitalization and opposite societal responses is complex and needs detailed analyzes related to the results of digital farming. At this point, digital twin technologies and methodologies help to discover the discrepancies that accrue as a result of the alternative applications. Especially, the evaluation and the forecasts of the results of the external effects that smart technologies may need to be discovered through the methodologies like a digital twin. Finally, the policies that are generated must lead to the necessity to use agricultural digitalization.

Different social science, natural, and technical science methodologies and technologies promote digital agriculture to force it beyond the prototype and experimental stages. Using digital twin methodologies with social sciences, natural or technical sciences can help to improve digital agriculture while responding to the social effects to increase the advantages and decrease the disadvantages of using these emerging technologies [36].

4.3 Transportation

Transportation has an inevitable role in daily modern life in different areas, including micro and macro scale integration that satisfies all the demanding systems. Using modern technologies in transportation capabilities enables the construction of sustainability, digitalization, and information exchange. Moreover, this capability enhancement may boost ecosystem safety by integrating the outcomes of technology-dense auxiliary systems into the conventional components of different moded transportation [37].

Industry 4.0 technologies connect different industrial capabilities and enable them to have smart instruments, thereby improving the effectiveness and productivity of different activities. Thus, the systems are donated with five important characteristic abilities of Industry 4.0, digitalization, optimization, and product customization; automation and adaptation; human–machine interaction (HMI); value-added services and businesses, automatic data exchange, and communication.

The Industry 4.0 concept takes advantage of DTs as the simulation of real systems for predictive analytics. DTs may include other technologies for the analysis of performance in hypothetical situations. But, the integrated use of DT with other Industry 4.0-related technologies is still developing. The DTs can also be used for the design and use of smart vehicles in the industry [38]. The essentials of DT are suitable to design with the combination of blockchain, forecasting techniques, and DT technologies. For example, a conceptual model can be applied to transportation use cases considering smart logistics and railway predictive maintenance [39]. Some other examples of DT applications may be: the use of different aspects of smart vehicles with DT technology to evolve over the years [40]; using DT to provide the companies with safe working conditions for railway workers [41] and safely benefiting automated guided vehicles [42].

4.4 Healthcare

The world population has increased at a steady state during the past two or three centuries [43]. It is expected to improve treatment methods and the quality of services in the healthcare field. In addition, the COVID-19 pandemic increased this pressure. As a result, healthcare has become one of the most critical social and economic challenges. To address these challenges, it is required a fully connected healthcare system which includes decentralized clinical trials (DCTs), mobile personal emergency response systems (mPERS), and remote patient monitoring (RPM). With the use of the Industry 4.0 concept, the healthcare system is equipped with new devices, such as smart monitoring devices, smart wearables IoT devices, RFID devices, and medical robots, as well as emerging technologies, such as, artifical intelligence, medical data analytics, cloud/edge computing, and decision support techniques for interconnected healthcare intelligence. With Industry 4.0 and related technologies, healthcare is called as Healthcare 4.0, which is the new area for the healthcare sector and advanced applications. Smart and connected healthcare consists of diverse healthcare facilities (e.g., hospitals, disease specific facilities) as well as equipment and devices. This way the patient's environment including their homes and communities are connected together. Information about the patient including electronic health records (EHR) can be securely shared. Proactive treatment and preventive approach as well as personalized medicini can be utilized by the AI techniques [44].

4.5 Manufacturing

Various manufacturing operations have the presence of digital twin methodology in their processes. One of them is using digital twins for maintenance applications in different industry sectors, mostly in energy, aerospace, and manufacturing sectors, usually in areas where the maintenance cost is higher than average [45]. The use of digital twins in maintenance and operations monitoring and optimization also provides engineers with the option to integrate not just the mechanical 3D virtual world but also the electrical and programming side, to enable easier programming and control program creation [46]. Some of the main applications of digital twins in manufacturing also mostly deal with production planning and control [47]. New requirements are placed on a typical manufacturing cell operation, driven by intelligent perceiving, simulating, understanding, predicting, optimizing, and controlling strategy [48]. In this way, knowledge is created dynamically in real-time and can provide companies with more intelligent manufacturing strategies that can keep manufacturing systems more flexible and cost-efficient [48]. Another aspect related to the use of digital twin methodology in manufacturing is the creation of big data and the need for more reliable data processing and analysis and faster decision-making methodologies [46]. The application of digital twin technology in manufacturing also leads to the development of the ISO 23247 (digital twin manufacturing framework) standard [49]. Digital twin includes various components of real assets such as data, resources, applications, and monitoring metrics [50]. Also, the digital twin is used to support monitoring, maintenance, management, optimization, and safety in manufacturing systems [46].

4.6 Supply Chain

The supply chain concept has changed with the evolution and the impact of technology due to the increase in complexity and dynamism of the systems. The necessity to adopt a responsive and agile approach has forced companies to implement Industry 4.0 technologies and fundamentals. Industry 4.0 requires digitalization and digital analytics abilities for live event capture and taking appropriate measures, which are strongly related to DTs' area of interest [51].

The DT uses a simulation model of the real systems in order to enable new and improved technologies with reduced costs. However, despite digital twins' being popular nowadays, the use of DT in logistics digital twin and supply chain management is rare. By using the same methodology as in a manufacturing system that has different shop floors which transform the raw materials via different operations, a logistic system also can be simulated through the components of the logistics facilities with different forms of the products, beginning from the suppliers to the customers, including the activities of picking, moving, sorting, and shipping [52]. The DT is a virtual imitation of the supply chain, which contains many assets, facilities, logistics capabilities, and management systems [51].

The interest in the implementation of smartness in the supply chain and sustainability is increasing through their efforts to adopt smart technologies and applications of sustainability to these companies. Simulation, big data analytics and cloud computing are some of the known smart technologies that can be used with the sustainability measures like cost, lead time, damage, and loss for the integration with Industry 4.0 technologies in supply chain management [53]. For example, [53] use the best worst method (BWM) and quality function deployment (QFD) for the development of a hybrid methodology to determine the maturity levels and the smartness of a supply chain. A twin QFD methodology is made use of to generate the main components of a supply chain and the relationship among the supply chain activities, smart capabilities, and the performance measures in the supply chain. QFD-based methodologies can be applied to the strategic-making tools to design supply chains with smart and sustainable capabilities. Best worst method (BWM) is a methodology developed by [54] as a new multicriteria decision-making technique that helps managers in the selection of different alternative systems considering the related criteria.

In Industry 4.0, the integration of information and communication should be implemented in all directions to foster the companies to increase economic earnings such as competitiveness, productivity, and profit. The integration of information and communication with end-to-end engineering through all the phases of the product lifecycle will enable the companies to apply the basic concepts and innovations to the supply chain through Industry 4.0 technologies.

4.7 Facility Management

The operation and maintenance (O&M) phase of a building's lifecycle are the most expensive [55, 56]. Various researchers are focusing on integrating the use of digital twin concepts and the building management systems (BMS) used for facility management [56]. Some examples of digital twin applications are planning and tracking the ongoing occupancy and cleaning activities in office buildings during the whole building lifecycle [56]. The rise of the digitization and computerization of various stages and processes of built environments are now driving the ways how architecture, engineering, and construction (AEC) projects are planned, built, and managed [57]. Centralized data from various systems within each building can lead to more responsive decision-making processes related to more predictive space management, organization, and cleaning, all for better cost and space allocations and easier planning and delivery of customized cleaning activities and contracts [56]. Other researchers are focusing on using digital twin concepts for the future comprehensive facility management solution that can help monitor, detect, record, and communicate asset anomalous issues [58]. Another application can be related to the easier sensor fusion of different devices that are used in facilities to monitor indoor air quality (IAQ), carbon dioxide, temperature, humidity, and volatile organic compounds (VOC) levels, all for the purpose of more accurate and responsive environmental and health planning [56].

4.8 Smart Cities and Connected Communities

An increased need for Internet of things (IoT) applications in the various different areas related to the smart city management of multiple systems, operations, facilities, and processes has led to rising of the use of digital twin concepts for the large-scale replicas of actual systems that are in real cities that can serve as a base for the data that is used for a plethora of decision-making processes [59]. Some examples of the use of the digital twin concept for smart cities are the interactive planning platform for city district adaptive maintenance operations, consisting of a multilayer geographical system that receives data from the various heterogeneous data sources that are created by the multiple urban data providers. The main purpose of such integration is to provide one source of data that can be analyzed and used for more accurate predictions related to urban activity levels, and they can serve the communities as an accurate source for better and more responsive planning, scheduling urban maintenance operations, and interventions [60].

5 Discussion

It is an industry age being supported new innovations, technologies, and applications in almost every industry, from energy, agriculture, transportation, healthcare, manufacturing, and supply chain to many more. Industry 4.0 is the main driver with support for its enabling technologies, such as cloud computing, the Internet of things (IoT), and cyber-physical systems. In the industry, cost and maintenance are two important factors to operating the system properly in terms of reliability, availability, security, and efficiency. Industry 4.0 is a perfect concept to achieve these goals. However, it can be costly and complex to adopt the Industry 4.0 concept, especially the integration of real physical devices. Therefore, a virtual environment needs a digital copy of the real system to create operations and production problems, digital twins.

General observations regarding the digital twins for Industry 4.0 and beyond applications can be summarized below.

- *Observation 1*: Digital twins can significantly contribute to Industry 4.0 and beyond applications by increasing the reliability, availability, security, and efficiency.
- *Observation 2*: Industry 4.0, along with digital twins, can boost the technology industry from the Internet of things (IoT), cloud technologies, big data, data science, virtual reality, artificial intelligence. additive manufacturing, predictive maintenance, and many more.
- *Observation 3*: Digital twins will bring several challenges due to the need for rapid technology adoption.
- *Observation 4*: Digital twins will be used more in all different engineering processes and disciplines with Industry 4.0.

6 Summary and Conclusion

Data communication, processing, and computing technologies have been constantly changing with the industry demand since the early industrial revolution. Each term is called differently based on the demand or the innovation from Industry 1.0 to Industry 4.0. For instance, Industry 1.0 was a shift from a handicraft industry to a machinery industry, while Industry 4.0 promotes the computerization of manufacturing using advanced technologies, such as the Internet of things (IoT), cloud technologies, big data, data science, virtual reality, artificial intelligence, additive manufacturing, and predictive maintenance. It is crucial in industrial applications to optimize the real-time system, increasing reliability, and availability while reducing risks and maintenance costs. The digital twin is the replica of the real world in the virtual environment, which can address this issue through real-time data and information under the Industry 4.0 umbrella. Integrating the physical and digital world is one of the key features in Industry 4.0 to design, implement, test, and maintain the systems for long-run. These systems are usually costly and complex in terms of operation and testing. Digital twins can help to investigate and analyze them in a virtual environment by providing a virtual copy. This chapter discusses the applications and methodologies of the digital twin along with its importance in Industry 4.0. The digital twins will lead to significant shifts in Industry 4.0 and beyond applications for several fields, such as energy, agriculture, transportation, healthcare, manufacturing, supply chain, facility management, smart cities, and connected communities.

This book chapter is expected to give a broad vision to researchers, engineering, and experts in Industry 4.0 and beyond applications using digital twins and understand the digitalization and Industry 4.0 along with its enabling technologies.

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Digital Twin and Manufacturing

Ozgu Can and Aytug Turkmen

1 Introduction

This chapter examines the concept of the DT in the context of manufacturing. The chapter's objective is to present a comprehensive review of the key enabling technologies and DT in manufacturing application domains. Therefore, the chapter focuses on the technologies that are used in the DT, DT's integration in manufacturing, and the current state of the art in the related field. Also, challenges and future directions for the DT in manufacturing are discussed.

The process of digitization was made possible by recent technological advancements and developments, including the Internet of Things (IoT), machine learning (ML), Artificial Intelligence (AI), Cloud Computing, smart sensors, and other new generation technologies. These technologies also brought new opportunities for a variety of industries. Digital technologies enable network infrastructures-based remote sensing, monitoring, and control of cyber-physical manufacturing devices and processes. This makes it feasible to connect the real and virtual worlds directly. Consequently, the digital technologies and transformation of industrial production processes from design and engineering to manufacturing lead to Industry 4.0 which refers to the fourth industrial revolution.

Industry 4.0 creates an efficient, automated, connected, and intelligent ecosystem for industry. Autonomous robots, big data, augmented reality, Cloud Computing, cyber security, IoT, system integration, simulation, and 3D printing are the nine technologies that drive Industry 4.0. Achieving digital information technology, quick design modifications, and great adaptability are all possible with Industry 4.0's sustainability and next-generation intelligent manufacturing [1]. Hence, Industry 4.0 enhances the future of industries and increases the productivity and efficiency in

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_8

the manufacturing. Therefore, Industry 4.0 is a combination of modern information and communication technology and industrial practices [2].

In today's competitive environment, this digital transformation in manufacturing is accepted as an opportunity to reach higher productivity levels. Therefore, operations in manufacturing systems are digitized. As a result, the global manufacturing sector has undergone industrial revolutions like mechanization, electrification, and information related to this digitalization and the ongoing development of communication, information, and automation technologies [3]. Moreover, the use of digitalization technologies enabled various industrial sectors to virtually represent their products and plan their processes in manufacturing. Thus, industrial products are produced using digital technologies and machinery throughout their entire life cycle. Therefore, different types and large volumes of data are produced.

Every step of the manufacturing process involves the collection of enormous volumes of data, which are then used for real-time planning. However, this leads to low efficiency and low utilization due to the isolated nature of these valuable data [4]. Therefore, these valuable data need to be processed and analyzed by simulation-based solutions. Simulation-based solutions are applied to optimize operations and predict possible errors during the production operations. Therefore, simulation is a powerful technique for a system's early planning stages of verification, validation, and optimization [4]. The idea of the Digital Twin (DT), which is regarded as the simulation of the system itself [5], has been revealed as a result of the significance of the integration of the physical world and the digital world. Therefore, DT is used to empower the manufacturing systems and various industrial sectors.

The Digital Twin is a representation of a physical thing, process, asset, system, or service in the actual world. DT reproduces the physical entity accurately in the digital world and enables an effective monitoring, prediction, and optimization of the related physical entity throughout its life cycle [6]. For this purpose, DT uses real-world data to create simulations. In the manufacturing, DT focuses on the Asset Life Cycle Management (ALM) that is shown in Fig. 1 to optimize the life cycle of an asset. Therefore, the DT can predict how a product or process will perform in the production and how this process will progress. Thereby, each life cycle phase of the manufacturing system's operations can be optimized by DT. In addition, possible outcomes are evaluated before any cost loss occurs and problems are identified before starting the production process. Thus, efficiency is provided and higher volumes of manufacturing are ensured. In this way, DT bridges the gap between physical world and cyber world and constructs cyber-physical systems in manufacturing [7]. As a result, DT has the potential to change both the present and the future of manufacturing [8].

DT transforms the future manufacturing landscape by providing the necessary technology to create smart manufacturing that is fueled by digital twins. According to market data released in [9], the size of the global DT market is anticipated to reach $63.5 billion by 2027, growing at a rate of 41.7%. Besides, due to the COVID-19 pandemic, companies are now choosing to operate with least manpower. Also, the manufacturing has the largest share in the industry segment of the global DT market. The market research further indicates that the primary end users of DT technology

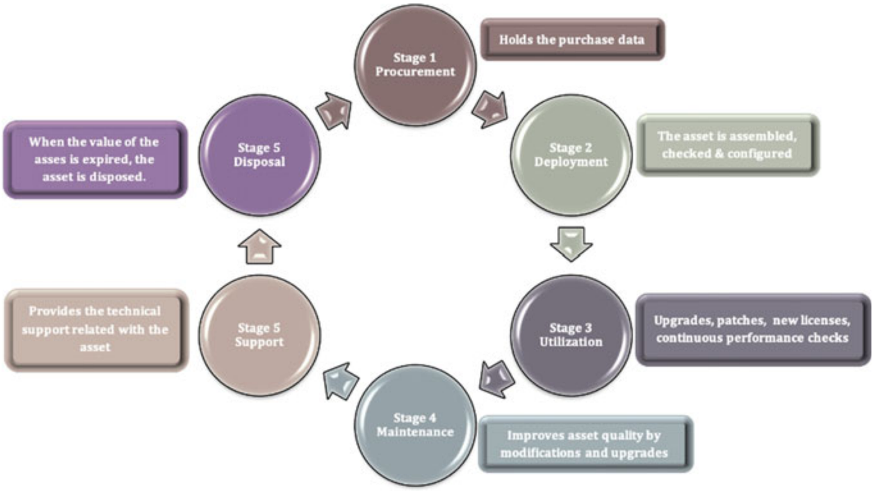


Fig. 1 Asset life cycle management

in manufacturing are the energy and power, automotive and transportation, and aerospace and defense industries. The increased demand for predictive maintenance, real-time data monitoring, real-world use cases, and improved decision-making are the prime reasons for the growth of the DT market.

The remaining parts are organized as follows. The historical context and an overview of the Digital Twin concept are provided in Sect. 2. The numerous Digital Twin components and manufacturing applications are highlighted in Sect. 3 along with its application areas. In Sect. 4, Digital Twin application examples in various industries are presented. Section 5 discusses challenges, future directions, and open problems that need to be tackled for an effective and productive adoption of Digital Twin in manufacturing. Also, conclusions are presented in Sect. 5.

2 An Overview of Digital Twin

The Digital Twin provides a digital representation of a physical object. As a result, the DT develops a living model of the physical product throughout its existence and enhances decision-making by offering data on dependability and maintenance. In order to prevent issues before they arise and to plan for the future using simulations, the physical and virtual worlds are combined.

The DT has gained significant importance due to Industry 4.0 and technologies such as machine learning, IoT, and Artificial Intelligence. The emergence of DT is a result of the development of the concept of "digital production" and the Industrial IoT [10]. The idea of DT is not new. The DT technology is based on the existing technologies such as simulation and digital prototypes. DT is stated as the next wave

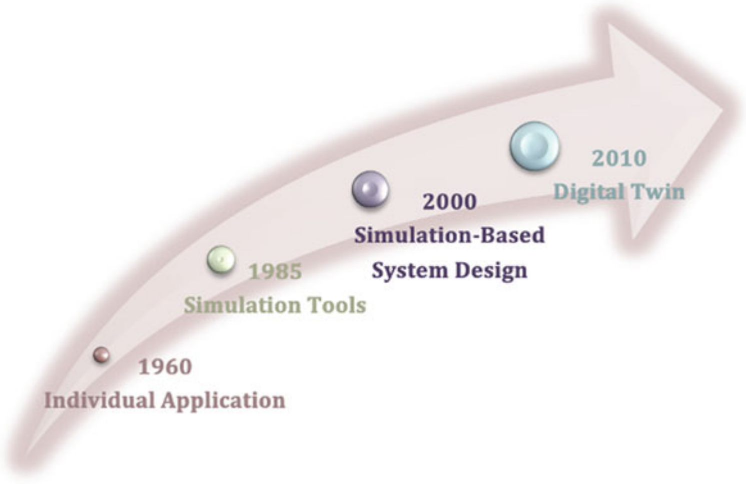


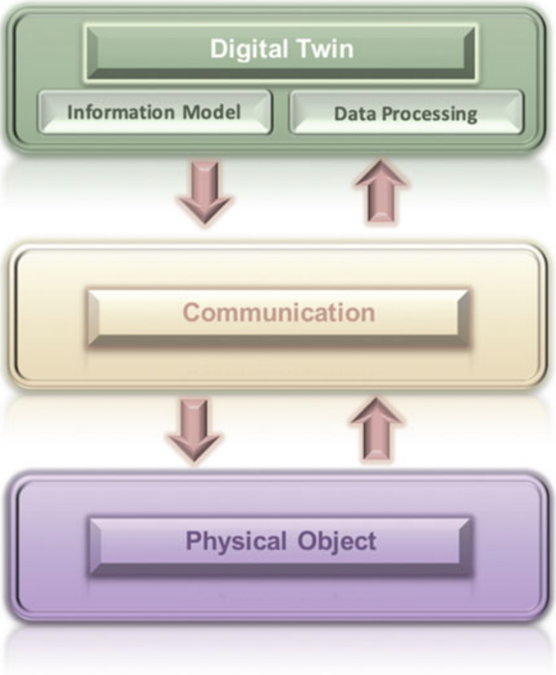
Fig. 2 Digital twin as the next wave in simulation

of the modeling and simulation technologies [11] as shown in Fig. 2. Today, the DT is a more important topic and has become more widespread. Therefore, it is applied to various fields, such as manufacturing, healthcare, retail, and supply chain. As companies are now digitizing their operational processes, the market size of the DT is increasing in worldwide. The size of the global DT market was estimated at USD 3.1 billion in 2020, and by 2026, it is expected to have grown to USD 48.2 billion [12]. Hence, the DT is considered to be one of the ten most promising technical advancements for the coming 10 years [13]. Also, the DT is predicted to have a major role in the future for the defense and aerospace industry [14].

The first use of the DT concept dates back to 2003. In 2003, the DT is introduced by Michael Grieves at his Executive Course on Product Life Cycle Management (PLM). Later, Grieves classified the DT into three subtypes: (i) the DT prototype, (ii) the DT instance, and (iii) the DT aggregate [15]. In 2014, Grieves indicated three main parts for the DT in a whitepaper [16]: (i) a virtual product, (ii) a physical product, and (iii) a connection of data and information that ties the virtual and real products. Also, the development of the DT technology needs three components that are shown in Fig. 3 [8]: (i) an information model, (ii) a communication mechanism, and (iii) a data processing module. The data processing module uses information from heterogeneous multi-source data to create the live representation of the physical object, while the information model abstracts the physical object's specifications and the communication mechanism transmits bidirectional data between a DT and its physical object. These components must work together to construct a DT [8].

The five-dimension DT model is proposed in [17]. The proposed model improves the aspects of production, operations, and business processes. As shown in Fig. 4, the five-dimensional conceptual model of the DT consists of virtual models, data, physical entities, services, and connections [17].

Fig. 3 Components of digital twin [8]



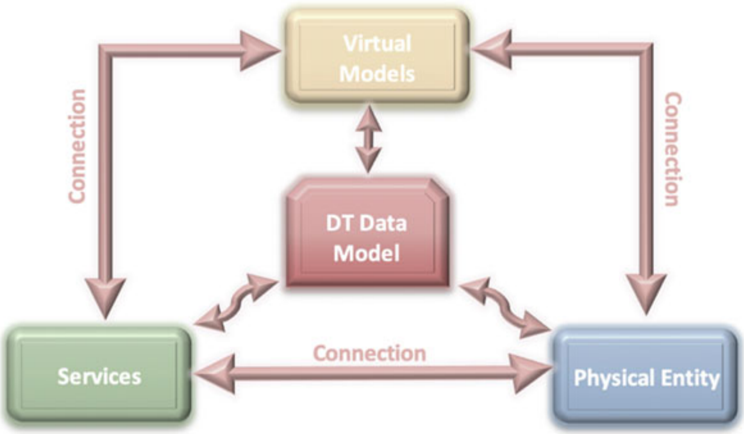


Fig. 4 Five-dimensional conceptual model of digital twin

The physical entities represent a physical object that is tangible and visible. The DT creates the virtual model of the physical entity. Physical entities provide the collection of various parameters through sensors. Thus, the collected data is used to create the virtual state of the physical entity.

The virtual model is the digital model of a physical entity. An efficient IoT infrastructure is needed to increase the accuracy of virtual assets and to ensure the compatibility of virtual and physical assets.

The DT deals with large, multi-source, multi-temporal, multi-dimensional, and heterogeneous data [17]. This incoming data is used by various algorithms to make decisions. The data model can be obtained from multiple data sources, physical and virtual assets, services, and knowledge that is extracted from domain information.

Services include all functions of the DT. Functions that are provided by the DT are presented through interfaces. The main feature of services is to receive data from sensors and process these data. The DT offers users platform services, third-party services, and application services. Application services include simulation, verification, monitoring, and optimization (such as customized software development, and service delivery) [17].

Virtual entities, physical entities, and services connect with each other to form the structure of the DT concept. For this purpose, information flow is established between physical entities, virtual entities, and services by connections. This connection between, virtual entities, services and physical entities is crucial for accurate analysis in the DT process.

3 Digital Twin for Manufacturing

Manufacturing refers to transforming raw materials into finished goods. Manufacturing also enables more complex products to be produced by selling basic goods to manufacturers. Thus, manufacturers can produce these complex products such as cars, airplanes, or household appliances. In recent years, global competition in manufacturing has accelerated as a result of technological advancements, product diversity, and the increase in market needs. Thus, the intensification of global competition has enabled manufacturing to evolve from traditional production processes to smart production processes. Further, several sectors in manufacturing aim to reach qualified products, efficient and effective services at less cost and in less time by integrating new technological developments. Therefore, the DT is a key concept for smart manufacturing as it enables interaction between the virtual and physical worlds. The benefits of the DT technology make DT the most powerful and intelligent consultant in the industry [18]. The major utilities of the DT are given in Fig. 5 [18]. Therefore, the DT can be used to train employees, plan the innovation, identify errors and avoid them, utilize optimization and risk management, and also provide a virtual platform for learning.

Digital Twin technology enables manufacturers to better understand and analyze their products in product design, real-time simulation, tracking, and optimization. In

Fig. 5 Major utilities of the DT [18]

the real world, performing tests on complex products is costly and difficult, whereas using DT allows the product to be easily tested before presenting it to the physical world. The DT also reduces the operational costs and potential capital costs, extends the life of assets, optimizes the operational performance, and improves the optimization and preventative maintenance over the changing conditions. The product design, real-time monitoring, quality management, predictive maintenance, and production planning enable DT to improve operations in manufacturing.

3.1 Product Design

In the design and product development processes, the DT is commonly used. The DT enables to create virtual prototypes during the design phase. Thus, it is used to test different simulations or designs before investing in the final product. Therefore, deficiencies of the product are being determined before the production by analyzing whether the product designs are efficient or not, especially for a product with a complex manufacturing process. Consequently, possible results will be evaluated without any cost. Moreover, any problems that may occur will be detected before starting the production. Hence, DT saves time and money by reducing the number of iterations that are required to put the product into the production process, iteratively modeling changes, testing components and their functions, and troubleshooting malfunctions. Also, Digital Twins and XR technologies can be combined at the product modeling phase to produce high-quality designs. This makes it possible for all stakeholders, including managers and customers of digital twins, to monitor each stage of the product design process in detail and find solutions rapidly.

3.2 Real-Time Monitoring

Digital Twin is a real-time virtual representation of a product and an operational process. Instant data flow is provided to the DT through sensors that are placed on physical objects. The production is monitored in real time with this instant data flow. Therefore, problems in the production life cycle can be identified, and strategic decisions can be made by directly intervening in the production. Thus, monitoring the DT production performance in real time helps pre-planning and optimizing workflows. In addition, the DT can also be used to analyze data retrospectively to make predictions on future productions.

3.3 Quality Management

Quality management is an essential factor in the manufacturing process. Monitoring IoT sensor data and responding to them are critical issues for maintaining quality and reducing bottlenecks during production. The usage of DT enables real-time analysis of data that comes from sensors. Thus, the product quality is improved at decreased costs by detecting the quality control problems immediately. Moreover, the DT data can also be used to detect reasons of the related problems. Therefore, in order to improve the quality of the production, the DT is used to model each part of the manufacturing process to determine which materials or processes can be used.

3.4 Predictive Maintenance

The DT determines variances that indicate the need for preventative repair or predictive maintenance before a serious problem occurs in the manufacturing process. In traditional approaches, processes of determining the malfunctioning of a machine/equipment, decision-making, and taking an action result in time loss. For this reason, the production volumes of enterprises decrease. Periodic maintenance of machine equipment can help prevent malfunctions, but it does not guarantee that the equipment will not malfunction. However, the DT collects real-time data via sensors to create a virtual representation of the machine. Thus, the status of the machine can be monitored in real time, and accurate forecasts can be done regarding the status of the machine. Also, the DT is used to optimize the load levels, tool calibrations, and cycle times of machines. Therefore, using DT enables enterprises to detect problems with machines that may arise and to implement predictive maintenance.

Businesses can predict when and where potential service breakdowns might happen and respond to them in order to stop any service interruptions by having robust predictive maintenance solutions in place. In machine learning and Artificial Intelligence, predictive maintenance refers to the ability to use a vast quantity of data to forecast and address future issues before they lead to operational breakdowns. Predictive maintenance uses sensor data to determine when maintenance is required in order to minimize downtime. Data collected initially by various sensors located on the machines are pre-processed. In a pre-processing step, significant features are retrieved from this data and used to train a machine learning and Artificial Intelligence algorithms system for predictive maintenance. Then, Artificial Intelligence (AI)-based decision support systems utilize these data. However, under normal fault circumstances, it is not always possible to collect data from field-based physical equipment. Also, equipment damage and catastrophic failures might result from allowing field failures to collect sensor data used to train AI and machine learning systems. It could be time-consuming, expensive to purposefully create errors under more regulated conditions. However, the creation of a Digital Twin of the equipment and the modeling of various failure scenarios can be used to create sensor data to address these problems. Thus, all possible fault combinations can be evaluated.

3.5 Production Planning

Production planning cannot be handled in traditional ways due to the complex nature of the manufacturing processes. Thus, planners may overlook the actual processing conditions when designing the process. The DT enables enterprises to make production planning by simulating the operation processes in a digital environment. Thus, the efficiency of the production plan that is tested in the virtual environment can be analyzed. As a result of these analyses, production volumes and profit rates can be improved by making changes in production plans. Furthermore, production time and cost can be reduced with the results of analyses. Besides, simulations that are tested in the virtual environment include parameters such as equipment failures and lack of personnel which affect the production flow. Therefore, simulations give more efficient and accurate results than plans that are done with traditional methods. Thus, businesses achieve success in today's competitive environment and gain an advantage over their competitors by creating stronger production plans.

4 Digital Twin Applications in Manufacturing and Industry

Digital Twin is evolving rapidly with the recent scientific developments in communication technologies, sensors, actuators and connected devices, big data analytics, the Internet of Things (IoT), data fusion techniques, and Artificial Intelligence algorithms. The ongoing digital transformation and smart technologies enabled the implementation of DT technology in the industry to grow exponentially. Also, the DT has an essential role in the Industrial IoT (IIoT) concept which connects machines to other machines and optimizes productivity to make smart factories. Industry 4.0 deals with two worlds: one is the "physical world" and the other is a "digital world" [18]. Industry 4.0 aims to combine the physical and digital worlds by establishing real-time communication between them. They would be able to communicate manufacturing data in real time due to this connectivity. Therefore, the usage of DT in product development and process improvement studies has increased. In addition, the global market for DT technology is also growing due to the increased need for low-cost operations, optimized control in process systems, and the shortened product time-to-market. The Digital Factory's methodologies and models are utilized for low-cost integration, and the Digital Twin is a significant future component of the Digital Factory [19]. As stated in [19, 20], Digital Factory can avoid 70% of the planning errors, increase the planning maturity by 12%, reduce 30% of the planning time and 15% of the change costs. For this purpose, several companies in various industries use DT technology for their production systems.

The DT is useful throughout a product's life span. Four stages represent the product life cycle for successful products [21]: Development/Introduction, Growth, Maturity, and Decline. The Development/Introduction phase is the awareness stage of the product, the Growth phase is the product branding and promotion strategies, the Maturity phase is the market competition stage and in the final Decline phase the product becomes obsolete [18]. The Product Life Cycle Management (PLM) improves innovation, reduces time-to-market, provides new services for products, and supports for customers [22]. The DT has a potential to solve data-driven problems that exist in PLM, such as data sharing and big data analysis. For this purpose, the stages of detailed design, conceptual design and virtual verification are used to divide the product design process into three sections [23]. In the conceptual design, the concept, esthetics, and the main functions of the new product are defined. The design and construction of the product prototype are completed in the detailed design. Finally, the DT-driven virtual verification is the evaluation and test phase to detect design defects and their causes for a fast and convenient redesign. As a result, the DT technology offers great potential for use in product design, manufacturing, and service. In the existing literature, there are various DT solutions that have been proposed for different industry examples and real-life examples in manufacturing. In manufacturing, DT technology is generally used in applications such as manufacturing schedules and management, manufacturing control optimization, cyber-physical production system (CPPS) and layout of manufacturing lines [24]. In [19, 25], the technical production planning issues in automotive industry and the automated creation of a DT of a Body-In-White (BIW) production system are presented. Similarly, a DT approach for production planning and control is presented in [26] with a case study featuring a manufacturer that provides mechanical parts to the automotive sector.

In the automotive industry, the DT technology is used for optimization purposes in the production statistics and user experiences of the product that emerges in the vehicle production processes. For example, Tesla creates the DT of each vehicle that it sells [27]. Sensors in the car are used to provide the stream data into each car's simulation in the factory. Artificial Intelligence (AI) is used to interpret these data and determine whether a car is working as intended or if it needs maintenance [27]. Therefore, Tesla constantly learns from the real world and optimize each of its cars individually in real time by merging AI and IoT with the DT. The usage of DT technology evaluates the engine life of the vehicle, mechanical aging, damage that may occur in possible accident scenarios, errors related to aerodynamic design, and makes the necessary improvements before the vehicle reaches the end user. Thereby, Tesla ensures the continuity in its customers' vehicles by regularly downloading the recent software updates to their vehicles. Another example in automotive industry that uses the DT technology is Maserati. Maserati uses DT to increase its production capacity and maintain the tailor-made production. As a result, Maserati developed the Ghibli DT using Siemens' DT technology, which was a perfect replica of the original [28]. Processes were optimized for this reason by using data from both the real and virtual models at the same time. The result was a 30% reduction in development time and a decrease in manufacturing costs. Moreover, the DT is also used in Formula 1 to improve performances and to help in making the right strategy decision. Further, the DT helps teams to prepare and optimize their operations by practicing their driving and learning things in a car simulator before hitting the racetracks [29].

Similar to the automotive industry, DT technology has also an important role in the aerospace, defense, and space industries. The DT is used to track and monitor the vital and critical parameters of aircraft, test, and evaluate tools to check the integrity of aircraft features, and also for capacity planning, real-time remote monitoring, and process optimization. Thus, DT is a vital technique for simulating, predicting, and optimizing the product and the production system over the whole product lifetime in the associated industries. Many aerospace and defense companies have started using DTs for these reasons in order to decrease unplanned downtime for engines and other systems, mitigate damages and degradations, accurately predict how long an asset will be useful, increase operational availability and efficiency of platforms by performing proactive and predictive maintenance, extend the useful life cycle of platforms, and lower the life cycle cost of platforms [30]. For example, Boeing has adopted DT to advance aircraft manufacturing and maintenance operations in both its commercial and defense businesses, and Lufthansa Technik's AVIATOR platform uses DTs and other advanced digital tools to alert customers to possible problems before they occur and to offer technical solutions to address these problems [31].

Industry 4.0 promises an improved productivity, increased flexibility, customization, and better quality in manufacturing [32]. In this context, manufacturing systems are updated to an intelligent level from knowledge-based intelligent manufacturing to data-driven and knowledge-enabled smart manufacturing [32, 33]. An important prerequisite for smart manufacturing is cyber-physical integration [33]. The cyber-physical system (CPS) is the integration of the physical world with the digital

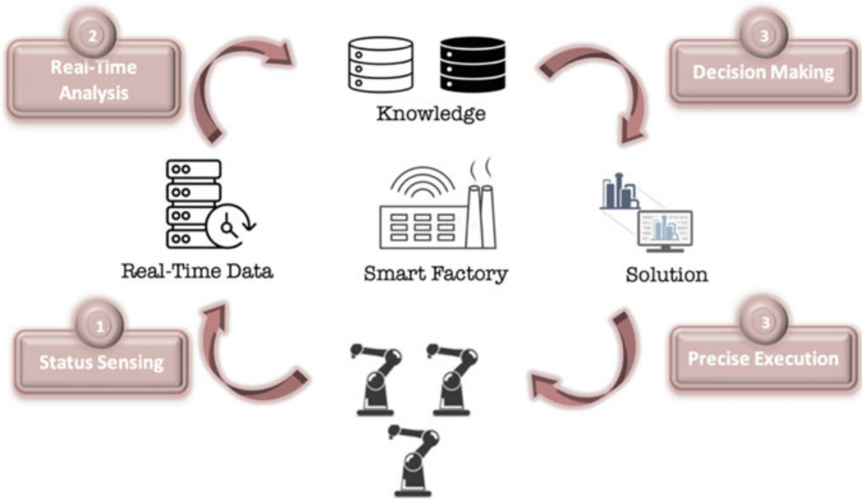


Fig. 6 CPS and DT for smart manufacturing [38]

world [18]. As seen in Fig. 6 [33], CPS and DT transform the existing manufacturing systems and enable smart manufacturing applications. The CPS consists of autonomous and collaborative parts and subsystems that are linked based on context within and across all production levels, from processes via machines up to production and logistics networks [34]. Smartness, connectedness, and responsiveness are the three main characters of the CPS. Hence, CPS is considered as a key feature of the Industry 4.0 [35], and the DT technology is accepted as a key enabler for realizing a CPS. A detailed discussion on the correlation and the integration of CPS and DT is presented in [33]. An information modeling approach to integrate various physical resources into CPPS via DT and AutomationML is proposed in [36]. In [37], the integration of CPS and DT is proposed, and a systematic framework is offered as a set of principles for quick system configuration and simple DT-based CPS runtime.

The DT-based approaches are used in various process manufacturing industries. For example, a framework is proposed in [38] to construct a DT-based approach for the petrochemical industry. For manufacturing simulation and control, the suggested DT architecture enables convergence between the physical and digital worlds. Similarly, the DT technology is also used in the energy sector for performance improvements, preventive maintenance, and repair works. Additionally, the cutting-edge DT solutions allow for changes in energy users' behavior to attain the necessary level of energy efficiency. A content analysis of the most recent energy research is offered in [39] with the goal of increasing energy efficiency. Furthermore, new generation power systems and the adaptation of the DT technology for power supply systems are presented in [40–43]. Also, energy forecasting studies based on the DT technology are proposed in [44–47] to ensure rational energy consumption and provide smart energy management system.

As a result, there are many actual instances of smart manufacturing facilitated by the Digital Twin. By fully utilizing cutting-edge information and manufacturing technology, smart manufacturing strives to optimize production and product exchanges [32]. Additionally, the use of intelligent sensors and devices, communication technology, data analytics, and decision-making models can facilitate the complete product life cycle. As a result, the DT enables real-time analysis of the past to forecast the future, enabling smart decisions to be made at every stage of manufacturing activities. This is the setting in which the DT plays a crucial role in smart manufacturing [8]. Thus, the effectiveness of the production and the quality of the goods and services will be increased, while production time and running expenses will be decreased. Besides, environment-friendly services for users are facilitated, and the market competitiveness of the manufacturing enterprises is improved [48].

5 Future Directions and Conclusion

The use of DT is anticipated to increase tremendously in the coming decades [49]. Also, the DT has enormous potential for changing the current manufacturing paradigm to one of smart manufacturing. Consequently, the DT is referred to as the leader of Industry 4.0 [39]. In this context, the DT enables to dynamically adapt to the changing environment, optimizes the production to respond changes in a timely manner, and improves economic benefits [38]. Thus, the DT technology is being recognized as a game changer in the manufacturing industry with the recent digitization process of manufacturing. Figure 7 presents the Strengths, Weaknesses, Opportunities and Threats (SWOT) of the DT in manufacturing.

The DT is an emergent technology, and the widespread implementation of the DT technology is increasing in various domains. Manufacturing is one of the main application domains among the DT applications. The DT technology is crucial in converting the conventional manufacturing system into a smart manufacturing system. The DT has the potential to develop into a significant technology for both research and application in the future, despite the fact that it is still in its early stages. Besides, the DT provides a substantial motivation for the future agenda of researchers and practitioners.

In today's dynamic environment, the DT is a promising and innovative approach for smart manufacturing. Moreover, the DT technology has an essential role in Industry 4.0 and the digitalization in manufacturing processes. The digital transformation in manufacturing reduces the production costs, increases the flexibility, and improves the productivity, the quality of products, and the efficiency of production process. The usage of the DT in manufacturing along with the advanced technologies such as smart sensors, decision-making models, data fusion techniques, big data analytics, simulation, Cloud Computing, Artificial Intelligence, and the IoT enables to facilitate of the entire product life cycle. Thus, manufacturers can monitor and optimize the production. The DT also offers special opportunities for value co-creation by assisting decision-making [50]. For this purpose, the DT reasons

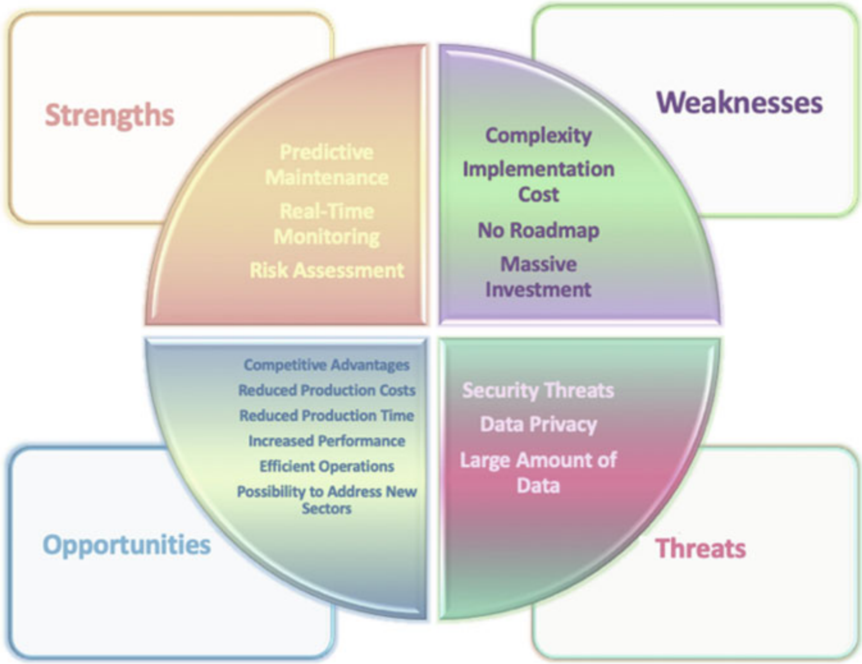


Fig. 7 SWOT analysis for the DT technology

why something might be happening, evaluates different alternatives, predicts the possible future outcome, and decides the action based on the objectives and preferences [51]. Thus, the DT improves the automated production planning, predictive analysis, real-time monitoring, and product optimization. Therefore, manufacturers gain an important competitive advantage against the dynamics and fluctuations of the global manufacturing market.

Several cloud service providers, such as Amazon, IBM, Microsoft Azure, provide “Container-as-a-Service” solutions for the development of Digital Twins. An Internet of Things (IoT) platform called Azure Digital Twins enables you to construct a digital representation of things, places, people, and business processes that exist in the actual world. Azure Digital Twins enables the creation of twin graphics based on digital models of all environments such as buildings, factories, farms, power networks, railways, stadiums, and even entire cities. These digital models provide better products, improved operations, reduced costs, and improved customer experiences. The “device twin” model is a component of the device management strategy used by Microsoft Azure IoT. The Device Twin is a JSON file that represents the device and provides information about its state. It changes practically quickly using data from the real system. When a device is connected to the Microsoft IoT hub, a device twin is automatically created. Azure IoT Hub is hosted in the cloud that serves as a central messaging hub for interactions between IoT applications and the connected devices. AWS IoT TwinMaker is a different Digital Twin platform that makes it simple for developers to generate digital twins of real-world systems like factories, industrial machinery, buildings, and production lines. Building Digital Twins can help optimize building operations, boost output, and enhance equipment performance. AWS IoT TwinMaker gives users the tools to do this. Customers can import pre-existing 3D models into AWS IoT TwinMaker to develop 3D representations of the physical system, which can then be overlaid with knowledge graph data to produce the digital twin. The Digital Twin is a JavaScript Object Notation (JSON) file that contains data, metadata, timestamps, and other essential information to clearly identify the connected device and is frequently referred to by Amazon as a device shadow. MQ Telemetry Transport, Representational State Transfer (REST) calls, or Message Queue Telemetry Transport (MQTT) architecture might all be used to provide near real-time communication. Also, the IBM Digital Twin Exchange is a platform that enables sharing of digital resources as Digital Twins between manufacturers, OEMs, and third-party content suppliers [52]. IBM is now targeting this business as a way to introduce intelligence, agility, and efficiency to a variety of sectors in light of the growth of digital twins. In order to digitize the real world, the new IBM Digital Twin exchange aims to bring together businesses and a variety of service and tool suppliers to build an app store. Industries with a high concentration of assets are the focus of the IBM Digital Twin Exchange, including manufacturing, oil and gas, civil infrastructure, automotive, etc. Customers may browse, buy, and download Digital Twin materials using IBM Digital Twin Exchange, a first-of-its-kind Exchange. The user interface on the Exchange isn't all that far from a standard e-commerce purchasing experience. The IBM Digital Twin Exchange's quick integration with ERP and EAM systems is a key benefit for customers.

On the other hand, various threats arise during the implementation of the DT. The DT is continuously fed with data via sensors to optimize performance, predict errors, and simulate future scenarios. Therefore, the automated process for physical asset data collection requires an efficient and robust IoT structure. A robust IoT infrastructure enables the DT to provide greater efficiency and more accurate results. Besides, the DT needs a noiseless and continuous stream of data to produce accurate results. Insufficient, inconsistent, and incomplete data cause the DT to produce incorrect results. Consequently, this also causes the results of the analysis to be inaccurate. Therefore, data quality has a significant role in the DT technology.

Further, privacy and security issues are the main challenges for the DT technology. The DT in manufacturing deals with large amounts of data that is provided by the IoT infrastructure. Besides, risks related to security, compliance, data protection, and regulations arise with the growing connectivity [53]. Also, the rise in cyber-attacks on critical infrastructures and sensitive data raises security concerns. Therefore, the relevant IoT infrastructure must meet the security requirements and be compatible with the recent privacy regulations. Another challenge is the lack of a standardized concept and approach in DT modeling systems. The lack of a standardized approach for the implementation of the DT concept causes the implementation process to be more complex. Universally shared use of digital twins throughout the entire product life cycle requires a standardized coherent framework that encompasses data flows, interfaces, etc. Thus, this is also an important research topic for future research in DT technology.

The concept of the DT has been around for a long time since it is introduced by Michael Grieves. However, in recent years DT technology has become a strategic technology trend in digital transformation. Moreover, the DT technology is working in integration with other technologies such as IoT, Cloud Computing, and Artificial Intelligence. Therefore, the DT is impacting several industries from many different areas. In smart manufacturing, manufacturers use DT to create products' designs, prototype their products, simulate their operations, and analyze production data and results. The DT enables interconnecting the physical and virtual worlds. For this purpose, the DT gathers all the interrelating data sources from an asset's entire life cycle [53]. Thus, operational processes and products that are risky and expensive in the physical world can be simulated in digital environments and analyzed and implemented in the physical world. Therefore, manufacturers improve their operational performance and business processes, save production costs and time. In addition, the Digital Twin will help to reduce IoT device development costs by accelerating the development of IoT devices. Thereby, IoT devices can be prototyped, the performances of these prototyped devices can be tested, and designs can be reshaped with the virtual world created by the DT.

Over two-thirds of businesses that have adopted IoT will have deployed at least one DT in production by 2022, predicts Gartner [54]. Furthermore, it is estimated that by 2028, the size of the global DT market would be USD 86.09 billion [55]. Additionally, the COVID-19 has accelerated the adoption of DTs in particular end-use industries and given DT adoption a boost to be better prepared for any future crises of this nature [55]. Figure 8 shows the global market size of the DT [53, 55]. Energy, automotive, transportation, aerospace, and defense industries are indicated as key industries among the end users of the DT technology [53].

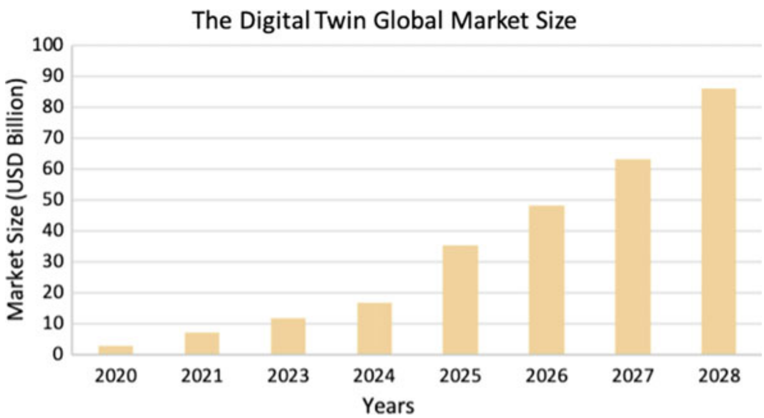


Fig. 8 DT global market size

Today's digitalizing world is reshaping the manufacturing industry. The use, operation, and maintenance of products after the sale are all being altered by the digitization of production. Additionally, the management of the manufacturing supply chain is changing as a result of digitization, as are the operations, procedures, energy footprint, and management of factories [56]. In this digitalization process of manufacturing, DT is a powerful tool for manufacturers to improve production lines, downstream operations, and to gain advantages in the global manufacturing competition. The DT technology, however, is still in its infancy. The DT faces several constraints and difficulties that must be overcome in order to realize its full potential, including financial burdens, the complexity of the information, a lack of standards, upkeep requirements, and regulations, and communications and cybersecurity-related problems [57]. Therefore, the DT concept provides new opportunities and motivation for future research initiatives. In this chapter, the fundamentals of the Digital Twin are discussed, along with how they apply to manufacturing. Additionally, a comprehensive analysis of the advantages, difficulties, and potential applications of DT technology in manufacturing is presented.

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Interoperable Digital Twin Solutions for Asset-Heavy Industry

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1 Introduction

Innovation, digitalization, and the use of modern technology are important components to scale and speed up future production facilities that are unmanned, lighter, smaller, robotized, and designed to achieve increased autonomy. Digital twin technology is at the core of the entire Industry 4.0 development process and is seen as the foundation for industrial digitalization efforts, delivering real-time insights, accurate forecasting, and intelligent decision-making by linking a physical system with its virtual equivalent. In fact, there are a plethora of benefits and advantages a digital twin can provide that may affect the whole organization by improving operational and asset performance, improving engineering and maintenance efficiency, detecting early signs of failure, and as such contributing to the avoidance of costly failures and downtime incidents. Despite their potentials, digital twin implementations on an industrial scale are still limited due to several challenges, which include interoperability and scalability issues.

1.1 Challenges Associated with Digital Twin Implementations for Asset-Heavy Industry

According to Grieves and Vickers [1], the basic concept of a digital twin model is still based on the idea that "*a digital informational construct about a physical*

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_9

system could be created as an entity on its own. This digital information would be a "twin" of the information that was embedded within the physical system itself and be linked with that physical system through the entire lifecycle of the system." The main challenge regarding digital twin adoption in asset-heavy industries is not the lack of digital representations of facilities and equipment. There are massive amounts of data around. Instead, the main challenge is that the asset data (i.e., various pieces of the digital twin) is partly locked into several different data systems/applications where the data is defined purely for an application purpose using the system'/applications' own languages, information models, interfaces, and access regimes with limited standardization [2, 3]. Examples are assets having different identifiers in different systems, different engineering unit codes for the same unit, different naming on the same type of attributes, and definitions that are hard to understand. Most asset-heavy industries are already exchanging massive amounts of data internally and externally across the value and supply chain of contractors, suppliers, service providers, partners, manufacturers, and integrators. However, very often there are human engineers in the loop doing manual translations to make things work. The integration costs are high and sometimes not technically feasible without impacting the fidelity of the data and context. Some of the information exchanged are also put into documents (for example, PDF, Word), instead of being in the form of structured machine-readable models. This is not scalable in a connected Industry 4.0 world, where we aim at increasing autonomy and cooperation between components [4].

Furthermore, current digital twins are the result of bespoke technical solutions that are difficult to scale [5]. For an industry with many assets or subsystems, performing forecasts or simulation poses a unique challenge since every subsystem has its own digital twin written in a specific software. One solution can be by using co-simulation. Co-simulation refers to an enabling technique, where different subsystems making up a global simulation are being modeled in one tool and executed in another, thus offering scalability [6]. Compared to more traditional monolithic simulations, co-simulation encourages re-usability, model sharing, and fusion of simulation domains. These are traits that serve the asset-heavy industry well, allowing the plethora of original equipment manufacturers (OEMs) and stakeholders to share content for the common good, without compromising internal knowledge in the form of black-box models, i.e., models with a known interface, but where the internal implementation details are inaccessible [7].

1.2 Elementary Aspects of Industrial Digital Twins

When physical assets are going to communicate and cooperate using the information exchanged, they need to be represented and connected in the digital world. Digital twins have been on the agenda of many companies in the last 5–6 years. These days company has a digital twin and/or a digital twin solution. The solutions are remarkably diverse and fragmented, and as such hard to grasp, because we rarely have a mutual understanding of what they are and what we are going to use them for

[8]. The recent joint whitepaper by the Industrial Internet Consortium (IIC) and the Platform Industrie 4.0 boils digital twins down to three elementary aspects [9]:

- A digital twin may contain *service interfaces/APIs* for other software to access the data, invoke commands, or run models. This enables connectivity and interactions between digital twins and various applications.
- A digital twin may contain a variety of *computational and presentational models* ranging from first principle-oriented (natural laws), data-oriented (statistical, ML, AI), geometrical (CAD) and/or visualization-oriented (AR, VR, 3D).
- A digital twin may contain *data* collected from and about its real counterpart, data that spans the full lifecycle of the asset, data on how it is designed and engineered, how it is manufactured, and how it is used in operations.

The whitepaper also highlights and illustrates the importance of interoperability to avoid information silos when implementing digital twins.

1.3 Solution Framework

In this chapter, we present interoperable digital twin solutions for asset-heavy industries based on the OPC UA and Asset Administration Shell (AAS). We illustrate in detail how to design, develop, and implement interoperable digital twin solutions with OPC UA-based AAS. We show the advantages of the proposed solutions by providing a case example from the ships industry. We describe two use cases: The first case is a robot in a shipyard, while the second case is a power train control system in a vessel.

The organization of the Chapter is as follows: We start by describing our interoperable digital twin solutions in Sect. 2. In Sect. 3, we define our work scope in asset-heavy industries. Section 4 describes the development of our interoperable solutions. In Sect. 5, we present two use cases, and Sect. 6 draws the conclusions and gives recommendations.

2 Interoperable Digital Twin Solutions Based on Asset Administration Shell

When information from a digital twin in Company A cannot be understood by applications or other digital twins in Company B, it becomes more challenging to realize use cases that involve several partners along the value chain. In the era of Industry 4.0, the data, information, and services in the digital twin shall, at any given time, be interoperable and available for exchange across the value- and supply chain in a uniform and standardized manner. This cannot be achieved if every company in each industry vertical is producing their own digital twin definition, their own digital language, and their own company-specific APIs/interfaces to access and utilize the digital twin.

A prominent definition describes interoperability as the ability of two or more objects from the same or from different vendors to exchange information and to use that information for correct cooperation [10]. Interoperability is so essential and important that it is one of the three pillars in the 2030 vision defined by Platform Industrie 4.0. Lack of interoperability in industry is a reality [11]. Many endpoints/interfaces provide data with limited context and defined in a vendor/system-specific manner. Standardized and machine-readable semantic dictionaries are key to achieve interoperability in Industry 4.0, and dictionaries like IEC Common Data Dictionary (IEC CDD) and eCl@ss are universally used [12]. Standardized APIs are the best and most acknowledged way to achieve interoperability across technical systems having different data models and formats [13].

The Asset Administration Shell (AAS) is, by Platform Industrie 4.0, being referred to as the standardized digital twin framework, the information backbone, and cornerstone of interoperability in Industry 4.0. Every asset in Industry 4.0 is surrounded by and represented in the digital world by an AAS [14]. An asset is anything having value to an organization, and it is common to differentiate between both tangible and intangible assets. The idea of the AAS is to systematically structure asset information and functionality in a uniform manner and to make information available and consumable from standardized interfaces/APIs along the lifecycle of the asset, not only within one company but across companies. The framework is applicable for horizontal integration across the value chain, to remove barriers and enable a data-driven economy between equipment manufacturer, supplier, sub-contractor, contractor, operator, and service supplier. The framework is also applicable for vertical integration connecting the plant floor with applications and services used for monitoring and optimization in the cloud, and it also enables end-to-end engineering covering the complete lifecycle with a closed loop between engineering and operations.

The AAS representing an asset is continuously updated and enriched throughout its lifecycle and supply chain starting with requirements and engineering. A manufacturer of an asset, e.g., a pump, provides a standardized digital representation, i.e., as an AAS, to the customers/end-users. The pump is then installed and starts operating on the facility, and the end-user can then derive and continue to evolve the AAS by including the usage and operational aspects. The pump asset is a part of a technical system also represented by an AAS. Different AAS will be able to reference each other.

In the era of Industry 4.0, use cases needing asset information and functionality will instead connect to the digital twin of the physical asset, which is the AAS. The use cases will be able to browse and read the relevant information using standardized APIs/interfaces and a shared digital language with semantic definitions. All the model transformation, information population, and information synchronization done between the various backend applications, and the AAS is hidden from the users of the digital twin. An AAS consists of a header (manifest, identification, etc.) and a body. The body is a "container" of digital models representing various aspects (aka. submodels) related to the asset, as can be seen from Fig. 1. The submodels gather

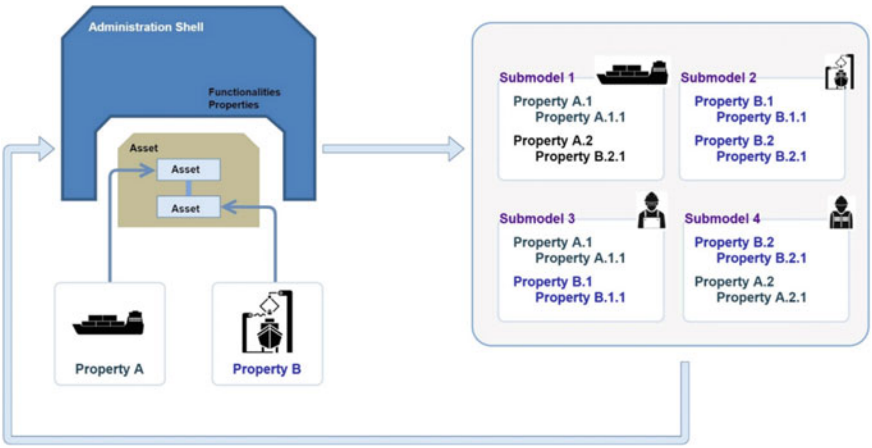

Fig. 1 A typical example of an Asset Administration Shell with a submodel definition

information belonging together. Examples of submodels may be (1) Identification, (2) Technical Information, (3) Maintenance, (4) Operational data, (5) Documents, (6) Energy efficiency, etc. In Industry 4.0, it is not enough with plain data; we need context and semantic interoperability. Each model element in the submodel shall therefore has a reference to its corresponding semantic definition (e.g., IEC CDD, eCl@ss).

The concept of submodels related to the same asset is beneficial to avoid an "information model war" where "my model is brighter than your model." In the AAS, there is room for all models because all models have their own purpose and use case. A process engineer, valve subject matter expert, safety engineer, maintenance engineer, integrated operations center, etc., will have different models and perspectives, and care about different data related to the same asset, e.g., a valve. What one engineer discipline thinks is a familiar model may to other disciplines be cumbersome. But, instead of keeping these perspectives disconnected in multiple information silos, the AAS is a framework that "connects the dots" and makes it consumable in a structured manner through standardized interfaces.

The AAS specification itself does not prescribe which and what content/submodels contains. An AAS is a meta-model, a framework. The content is modeled and realized through the submodels—and it should be use-case driven. The industry verticals/domains must shape and agree upon standardized submodel templates for similar aspects. If for instance each company is using proprietary semantic definitions and standards to define the maintenance submodel, we do not get cross-company interoperability even if AAS is used.

3 Scope of Asset-Heavy Industry

Engineering asset is considered a unit to reflect its economic value as a physical unit [15]. Heavy industries are commonly known as the most energy intensive, which are decisive for the realization of energy saving and emission reduction commitments. Therefore, the definition and level classification of the assets for heavy industries in the asset management system is the first step for the design of an interoperable digital twin. Here, we define five simplified asset levels referring to some existing research definitions [16, 17], which comprise our asset definition "Components to systems." In this chapter, the discussion and two related use cases are focusing on Level 3 in the following list:

- Level 1, Interfacing components like sensors and actuators
- Level 2, Core devices like drives, PLCs, computers, and switchboards
- Level 3, Single mechatronic system like wind turbines, vessels, cranes, trains, and robots
- Level 4, Single site, plant, or factory like wind farms, fleets, and ports
- Level 5, Highest asset level like smart city and metaverse.

In an asset-heavy industry, network structure and cybersecurity provide the connection between assets. They are also critical parts as well as assets to construct the work scope in an asset-heavy industry. The assets interconnect with IoT systems by communication protocols. The European Union Agency for Cybersecurity (ENISA) provides a list of main challenges in Industry 4.0 and Industrial IoT [18]. From a technology aspect, the interoperable framework is a recommended method to solve the cybersecurity challenge, in particular by integrating Industry 4.0 devices, platforms, and frameworks to existing systems. OPC Unified Architecture (OPC UA) is one promising standard in many asset-heavy industries. The OPC UA specification parts [19], which are OPC 10000-2, Part 2: Security Model and OPC 10000-18, Part 18: Role-Based Security, describe the details of the security architecture, implementation, and user management. OPC UA applications support username/password, X.509 v3 Certificate and JSON Web Token (JWT). The secure encryptions include "None," "Sign," "SignAndEncrypt" with different algorithms. In conclusion, the approaches consist of the configuration of server endpoints, secure encryptions, trusted clients, the Local Discovery Server (LDS) services, trusted servers, and digital certificates. They provide clients with sessions based on customized information within the security.

Table 1 Definition of the typical five groups

No	Predefined user groups	Typical defined user roles	Description
1	Designers and develop engineers	Designer, SW/HW developers,	Write and read, design view
2	Operators	Operators	Read, operational view
3	Maintenance engineers	Maintenance personnel	Read, engineering view
4	Document engineers	Assistants, test engineers	Write and read, documentation and test view
5	Operation managers	The manager of operators and maintenance engineers	Write and read, all views, the other group behavior data

4 Development of Interoperable Digital Twins

4.1 Design of an Interoperable Digital Twin

A key open issue to realize the full capacity of the IoT is interoperability. There are five facets of interoperability for an IoT system in IEC 21823 standard [20]: transport, semantic, syntactic, behavioral, and policy. Syntactic and semantic interoperability are analyzed in some papers by the transformation system use cases [21]. Furthermore, there are some typically defined user roles such as designer, SW/HW developers, test engineers, operators, and maintenance personnel for the simulation merges physical and virtual world in all life cycle phases [22]. Our interoperable design classifies several predefined data groups, which includes signals lists, access rights, and cybersecurity levels to help users access the raw data. For example, the definition of the typical five groups could be described as in Table 1.

4.2 Implementation of Asset Administration Shell

With the growing number of cyber-physical systems (CPSs) in industrial environments, the concept of industrial CPSs is evolving into a multifaceted, interdisciplinary, and comprehensive environment. This environment includes physical and computational elements combined with their digital representations. An asset administration shell (AAS) is a real-world application of the notion of a digital twin, and it can be accomplished by combining operational and information and communication technologies. It helps users, domain specialists, and system developers in converting raw data from physical assets into digitally comprehensible information. This is provided with an API through a secure communication protocol (e.g., OPC UA), which allows asset data to be accessible in the shell of an AAS. Using AAS, key assets properties, operational parameters, and technical capabilities can be defined in a standardized and interoperable manner, designed to facilitate seamless communication over standardized and secure protocols with other Industry 4.0 components.

According to the AAS model features, the submodel corresponds to a single asset piece of information. As a property, a SubmodelElement aggregates information about the assets in the submodel. The property contains definitions that are linked to a concept description and explanation, as well as a semantic specification. As a standardized implementation of a digital twin, AAS has the following strengths:

1. Making data more recognizable and hence decomposing information in the production process.
2. Providing cross-border interoperability by utilizing standardized APIs.
3. Serving as a foundation for future autonomous systems that do not require human input to coordinate and negotiate.

When the complexity increases in higher level assets, the interoperability is implemented by the microservice instead of by predefined user roles only. The user can freely choose the microservices only if he/she has access right. In this context, a submodel concept in AAS is a data view of information, such as an operational view, an engineering view, and a design view as well as the components collection. The consistency of the whole lifecycle makes sure that the design transfer phase knowledge to the maintenance phase with the asset signals mapping. Finally, the maintenance data is utilized for the future regular maintenance activity, to retrofit, and to optimize the product design based on the asset view. In the next section, we describe two concrete AAS implementation.

5 Experimental Case Study

In this section, we provide two case examples to show the development of an interoperable digital twin based on AAS in the maritime industry. In these case studies, we focus on a vessel in a shipyard with some existing applications and connections among all devices. We assume there are five user groups who need to customize the data service view (Sect. 4.1) and three communication standards (OPC UA, MQTT, and REST API). The two case studies are a robot in a shipyard (Sect. 5.1) and a power train control system in a vessel (Sect. 5.2) (Fig. 2).

5.1 Use Case 1: A Robot in a Shipyard

In robotic systems, digital twins can describe, control, and display the behavior of real objects. A huge part of this process involves creating a dynamic model of the object for use in simulation programs. In the case of robots, the current trend is for companies such as car manufacturers to plan, install, and program robots to perform

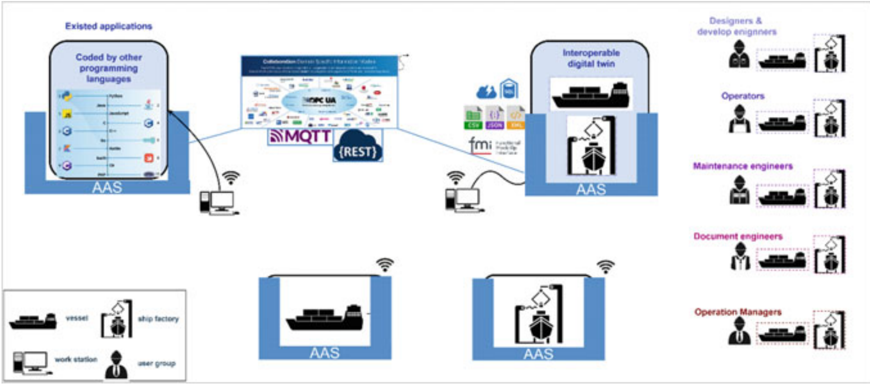

Fig. 2 Overview of AAS application in maritime industry

tasks on the factory floor which is costly, and it is not always certain that an optimal solution is deployed. For robotic arms to be used in manufacturing, they must not only be able to perform tasks efficiently but also be able to adapt in real time to changes in the environment. To have this ability and tap into the full potential of these devices, artificial intelligence needs to be applied and trained properly, and the implementation of digital twins is one effective way of supporting this training.

Robotic arms, as a use-case example, are simply divided into components such as controllers, base, arms, end effector, drives, and sensors. The AAS structure for this robotic arm can be implemented in AASX package explorer, an open-source application that provides a variety of functions to manipulate AAS data. Figure 3 shows an example of AAS for this use case represents an asset with its submodels and properties. Here, the submodels are component collections, which are controller, base, arms, drives, sensors, etc. The design is more suitable to make AAS for existing applications because it is just focused on the assets or functions themselves.

5.2 *Use Case 2: A Power Train Control System in a Vessel*

The concepts and methods noted in the previous subchapter are similarly applied to a power train control system in a vessel, as well as the typical application of robot arm in factory automation. In the marine industry, a seagoing vessel has a representation of its digital twin. It has a typical length between 45.72 m and less than 80 m, less than 500 GT (Gross Tonnage), and is not a Cruise Ship type as International Maritime Organization (IMO) defined. Until 2021, about 40% of the world fleet by principal vessel type is bulk carrier [23]. Nowadays, most of the new type zero mission, autonomous seagoing vessels are fully electric propulsion ones [24, 25].

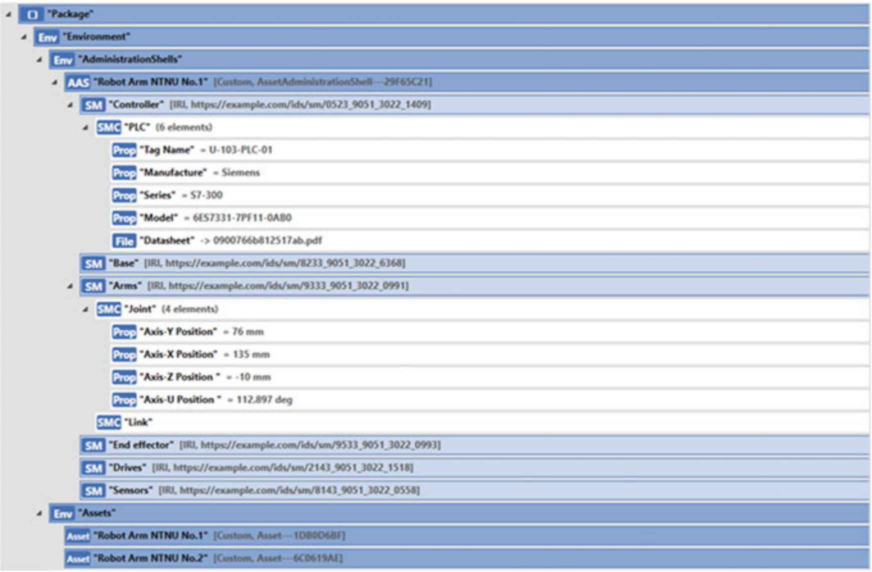

Fig. 3 AASX file structure for a robot arm in the shipyard

The power train control system is the core of the electrical system for an electric propulsion seagoing vessel. In our use case, a bridge, two sets of drives and motors (steering and propulsion) make up the main parts after the simplification. All these three types of devices are connected via an edge gateway (AAS hardware and software) to the AAS cloud platform like eCl@ss online [26]. The vendors VA, VB, VC are correspondingly the manufacturers for them as Fig. 4. All raw signals are approached and read and written without any delay time and disturbance.

The bridge has a lever, mainwheel, remote control system, weather station, and communication system. The drives accept the steering and propulsion command as well as the torque and speed control mode from remote control system. Afterward, it drives the corresponding motors with the power output; meanwhile, it returns the actual values and the status like currents, voltages to remote control system. The sensors of the motor will also collect the signals in parallel.

For applications, the machine learning engineer from bridge vendor VA is designing a predictive program, which could automatically calculate how much time the vessel will arrive at the destination. For user roles, the maintenance engineer from motor vendor VC is going to decide the maintenance or even retrofit schedule (the time, spare parts, etc.) for the motors. Both requests need access to the data of the whole parts of power train control system with professional and customized view. We assume they have basic knowledge of interoperable digital twins with professional data processing and programming skills. If it is a normal digital twin system, they must spend much time to filter and get access for the data of other subsystems (for example, access the motor data for the machine learning engineer, access the bridge

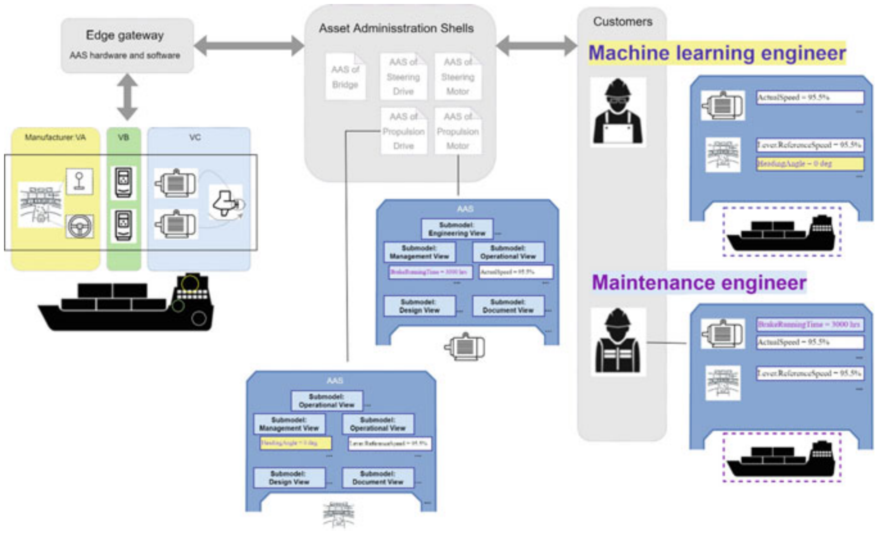

Fig. 4 An overview of the example application

data for the maintenance engineer). However, the interoperable digital twin could bring them the convenience of choosing the data service they granted. To protect their own raw data and avoid the inevitable misunderstanding, the asset vendors used to allow the other vendors to subscribe the data as an operator (the operational view). Examples are the running time of the brake of the motor used for maintenance is normally excluded in the operational view for the asset motor. Meanwhile, the heading of the ship used for route prediction is excluded in the operational view for the asset bridge. However, the engineers have some common data access requests like motor actual speed and the lever command for the drive. If we consider the complexity due to the variety of platforms and tools, the system scale and cybersecurity aspects, it is critical to have interoperability for asset-heavy industries digital twins with new standards.

Figure 5 demonstrates the example of the two use cases in OPC UA-based AAS. A1 and B1 are the AASX file defined on the assets. The submodels in A1 are defined as assets and functions while the ones in B1 are the user roles. A2 and B2 are the loaded OPC UA namespace in UaExpert software, which is provided by our AAS demo. A3 and B3 are sample variables with their value. This result means any OPC UA client could access the OPC UA server interface our demo automatically created by the AASX files like any other OPC UA servers. This is one typical interoperable digital twin implemented.

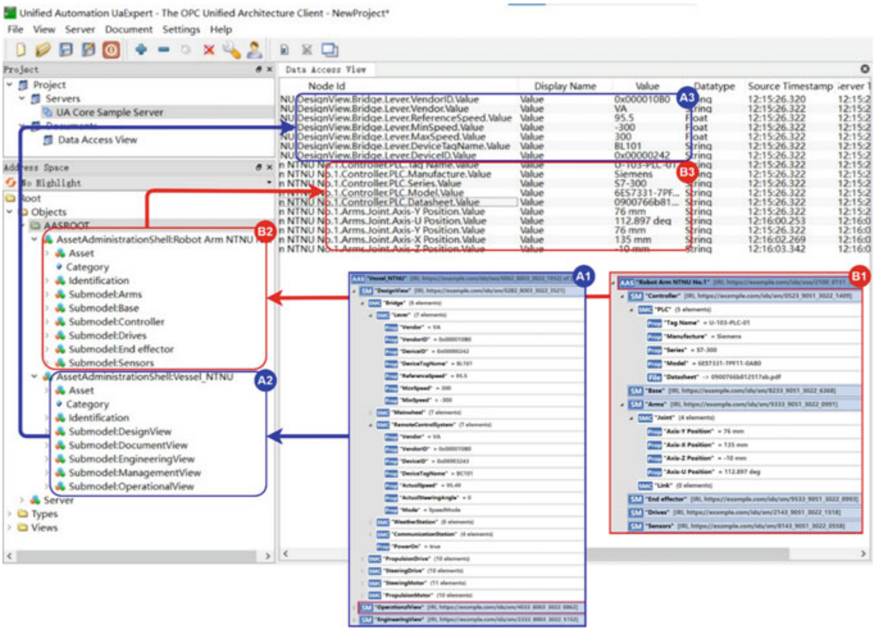

Fig. 5 OPC UA-based AAS implementation example, which consists of a robot (red) and a power train control system in the vessel (blue)

6 Conclusions and Recommendation

In this chapter, we have presented information about the development of interoperable digital twin solutions for asset-heavy industries. The solutions are based on industrial standards such as AAS and OPC UA. The interoperable digital twin with an OPC UA-based AAS solution provides a seamless integration approach only if the digital representations of facilities and equipment are well organized and defined. Compared with other protocols, OPC UA has the flexibility as regards cybersecurity, asset definition, data access management, etc. Two case examples in maritime industry have been presented. In future work, the interoperability aspects can be further enhanced if we take more simulation models and supply chain information into consideration. Furthermore, powerful visualization tools and physics engines can be added on top of the platform to enhance the user interface and to model the behavior of the physical system.

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Digital Twin in Health Care

Sabri Atalay and Ufuk Sönmez

1 Background

The widespread usage of electronic health data has recently increased the use of computer systems and Artificial Intelligence (AI) in the medical field. With the use of these technologies, new options for treatment and prediction models will be developed, which are expected to be superior to conventional epidemiological and statistical methods. AI could be defined as a computer science based on the realization of performing human cognitive functions by computers. Machine learning, deep learning, "in silico" simulation models, and "digital twins" are some examples of specific AI implementations [1].

The Digital Twin (DT) can be defined in various ways; however, it is best defined as "*data integration in both directions between the physical and virtual machine.*" DT is at the fore among the implementations of the Industry 4.0 Revolution that was realized through advanced data analytics and Internet of Things (IoT) connection [2].

DT refers to a digital copy of an animate or inanimate physical entity. The aim of this virtual tool is to monitor, understand, integrate, and analyze its properties or simulate its behavior as well as to optimize its functions, design and control its process [3].

The DT terminology was first used in 2003 by Grieves and was then published as a white paper forming the basis of the developments on the subject. The National

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_10

Aeronautics Space Administration (NASA) published an article in 2012 with the title "Digital Twin Paradigm for Future NASA and US Air Force Vehicles" [4].

Chen defined Digital Twin as "*It is a computer model representing all the functional characteristics and interconnections of a physical device or a system*" [5]. Liu [6] introduced a more detailed definition, "*A Digital Twin is a living model of a physical entity or a system, which can constantly adapt to changes and predict the future of the corresponding physical response based on collected online data and information.*"

The "in silico" experiment or simulation includes computer-based examples to build the models. Then, experiments based on computers can be performed to conduct research in a virtual medium without human subjects. DT combines the existing data from the object to help the decision-making process. DT has been found efficient in transportation and industry, such as railroad fleets, gas turbines, and production lines. This advantage is the ability to retrieve updates from real-world objects, which allows the model to make a correct prediction and feedback directly to the real-world state to make operational changes [1].

It is expected that DT implementation will bring significant benefits in health care. DTs of humans have the capacity to collect and analyze physical and contextual data to improve the quality of life and increase wellness. In this manner, a stroke can be predicted before the occurrence, allowing prevention. Machine and deep learning methods can also be employed to detect lifestyles and to make potential health problem predictions. Also, data on the environment, age, and emotional state can be collected and analyzed to fully understand and describe the holistic conditions of a user [3].

Although the healthcare sector is among the areas where the use of DT implementations is expected to be beneficial, the use of this technology is still premature in the field of health care and the management of patients. However, developments in technology increase in devices compatible with the Internet of Things and cheaper costs, and the development of connection technologies has increased the interest in this subject. One of the future goals is the Human Digital Twin, which will perform real-time body analysis. Another implementation is the DT used to simulate the effects of certain drugs. Another is to use the DT to plan and perform surgical operations [7].

The introduction of digital medicine into our lives mainly occurred in 2007 with the introduction of mobile phones. The first developments in this field were with the use of pedometers to monitor physical activity, followed by the development of biosensors, continuous rhythm detection and heart rate (Apple Series 4 Smartwatch), electrocardiogram (AliveCor), continuous glucose monitoring that did not require fingertip measurement (Abbott Libre and Dexcom G6 sensors), oximetry for sleep apnea detection, and smartwatches for blood pressure measurement (Omron HeartGuide Smartwatch) [8].

DTs can show the things that are going on in the bodies of their real twins and can enable the prediction of the presence of disease by analyzing the personal history and available data such as time, location, and activity of their real twins [9].

DTs can also inform patients about customized recommendations to improve their health. For instance, they can mentor a person with diabetes by following their food intake, physical activity, and daily routines and offer suggestions for improving their quality of life by researching other Digital Twins with diabetes in the virtual world. DTs can also detect stress levels and identify causes of stress with sensors, provide recommendations on how to avoid or decrease stress, and can also detect emotional changes in real twins and provide feedback, such as listening to the favorite music of the real twin or participating in their favorite activities (e.g., dancing, watching movies, walking, etc.). Besides this, they can also help guide athletes with fitness training protocols and optimized performance based on personalized physiological, psychological, and contextual data [3].

The reasons for using DT in the healthcare sector can be roughly summarized as follows: (1) The health data of individuals and societies are increasing with the help of portable smart devices, cheap sensors, communication technologies, machine learning, Artificial Intelligence, and computer hardware. (2) Secondly, human and conventional medicine will ultimately reach the limits of complexity, performance, and speed. The large and continuous increase in knowledge in medicine has made it nearly impossible for healthcare providers to deal with this in their daily routine. Furthermore, healthcare employees face human factors such as fatigue, mood, and time constraints and factors such as time pressure and cost which also affect their decision. (3) There is a growing requirement for personalized treatment. Consequently, individual treatments and simulations of treatments and various tools, which can be employed to determine the prognosis, will take their place in the field of health care over time, as will be various clinical decision support systems that are currently being used [10]. Briefly, the cooperation of computer technologies and medicine determines the basis of smarter and more connected services in the healthcare field. AI is a computer system that can incorporate relevant data, make rational and logical decisions, and achieve the best possible result based on this. Machine learning (ML) is a crucial component of DT. It can be described as "*our virtual mirror allowing us to simulate our personal medical history and health status by employing the data-focused analytical algorithms and theory-focused physical data*" [11]. In other words, DTs use the inductive approach (i.e., the statistical models that learn from data) and the deductive approach (i.e., the mechanical models integrating multi-scale information and data) to provide correct predictions and to maintain or restore health [12].

A DT includes many dynamic and multidimensional parameters. Dynamic data refer to the data that make up the digital image of a patient, accompanied by available data and the continuously updated and collected data from a person's life (medical condition, living environment, drug tolerability). The multidimensional status of the data stems from the fact that these data come from different sources (e.g., data from the clinical data, social environment of a patient or from sensors). The dynamic and multidimensional nature of these data separates DT from other approaches such as clinical decision support systems, which analyze the diagnosis and symptoms of a clinical manifestation, along with historical electronic health record data, to provide recommendations used to help healthcare staff make the rightful decisions about appropriate tests and procedures. These recommendations are determined using appropriate software and rules and constitute the most important component of clinical decision support systems. However, DT is not a mere data collection method for recommendations; it also correlates these data with each other using algorithms to incorporate data into a simulation process with clinical and economic targets identified in a meaningful and purposeful way. The fact that DT provides the chance to perform a medical device trial or pharmacological treatment in a computer environment rather than in real-life conditions allows for faster and more cost-effective results also protecting the patient from possible harm [12, 13].

Computer models increase the possibilities of diagnosis and treatment. In this way, future treatments will be organized based on accurate model predictions to improve health, not on mere instant health data [12].

DT can be roughly categorized into three groups as *active*, *semi-active,* and *passive*. In this respect, a system in which a digital copy (Digital Twin) of a physical system (physical twin) is constantly updated with information and data gathered from the physical twin is an active twin; a system in which the data that change over time are collected, but analyzed after data collection rather than a continuous update, is a semi-active twin; and if the measurements of a physical twin that is not constantly updated and that includes modeling assumptions are used, it is possible to talk about a passive Digital Twin. Also, there may be hybrid systems in which only certain parts or variables of the DT are constantly updated with the data gathered from a physical twin, but some data are not updated [14].

Despite the great advances in biomedical advances recently, many patients do not respond to drug treatments, which is because genetic differences among patients who have the same diagnosis make diseases become more complex. This causes patients to remain untreated and increases relevant costs [13]. Modern medicine has difficulties dealing with this complexity because diagnostic kits are limited and have certain sensitivities and specificities. Digital and genomic medicine can fill this gap by monitoring, processing, and incorporating the large amount of information obtained from electronic medical records and wearable digital devices [8]. The purpose of DT systems is to create a computer copy of complex systems and to conduct various tests faster and more economical compared to in real life. Additionally, it improves diagnosis and treatment in the human example.

DTs enable the visualization of the virtual replica (twin) of the patient by analyzing large data with new technologies such as AI. In this way, they offer individual treatment options, providing opportunities such as seeing the treatment results and the course of the disease [10].

Recently, one of the treatment modalities discussed in medicine is the subject of individual medicine, which is based on the idea that better results can be achieved by individualizing the diagnosis and treatment and that each individual has different genetic and environmental characteristics and lifestyle. To do this, complex medical records of each individual (i.e., demographic and clinical characteristics, diet, immunological and neurobiological bioindicators, and imaging results) must be obtained, analyzed, and used in the diagnosis, treatment, and follow-up. A concept example of such an approach is given in Fig. 1. The data entered into the

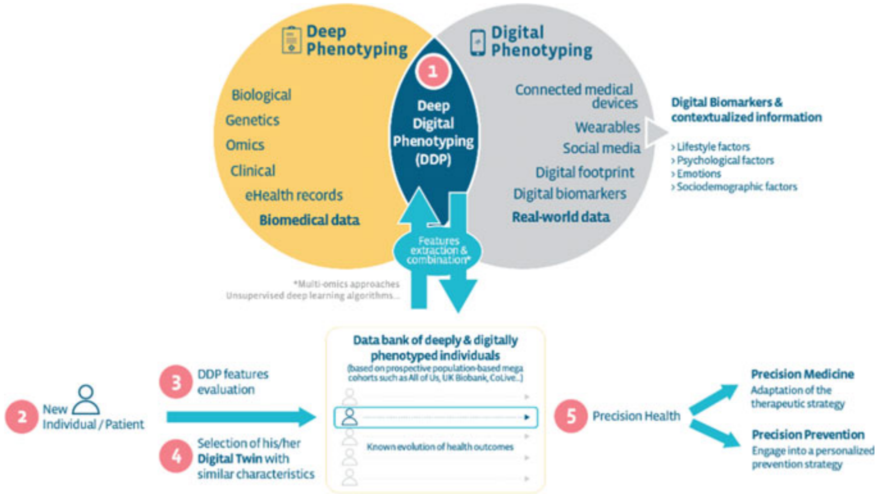

Fig. 1 Concept of deep digital phenotyping and digital twin identification for precision health [15]

system by the person online or with a cell phone or other electronic tools or obtained through connected devices are called "Digitosome" [15]. We have the appropriate tools to extract complex and large numbers of data with the aid of advances in deep learning algorithms and computer systems. For this reason, today, we can move from roughly layered groups to refined and small individual groups defined by multiple characteristics.

With the help of these data, a digital copy, in other words, a DT or a replica of each individual, can be created as the same or closely similar to that individual.

DT can indicate whether a medical treatment or device is suitable for the patient by simulating dose effects or device response before selecting a particular treatment modality [12]. The Swedish Digital Twin Consortium works to achieve the following targets for personalized health care for each patient; (i) creating unlimited copies (Digital Twins) of network patterns of phenotypic, molecular, and environmental factors regarding disease mechanisms; (ii) treat these DTs with numerous drugs in computer medium to identify the ideal drug; (iii) treat the patients with the drug that is found to be effective. The Digital Twin concept for personalized medicine is presented in Fig. 2 [13].

DT implementation in health care shows great promise. A large number of medical errors associated with diagnosis and treatment, poor resource use, inadequacies in workflow, and insufficient time for patients and physicians necessitate the use of such technologies [16, 17]. Artificial Intelligence-based deep learning networks are expected to assist in interpreting medical images, dermatologic lesions, retinal images, pathology slides, endoscopy, electrocardiograms, and facial and vital signs [18]. It is also expected in the future that many healthcare professionals, from specialist physicians to paramedics, will use these systems.

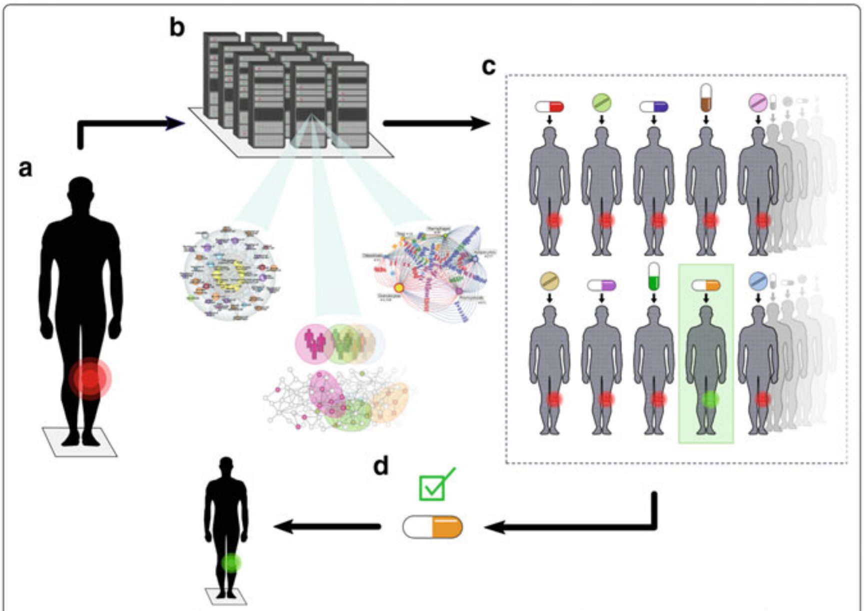

Fig. 1 The digital twin concept for personalized medicine. **a** An individual patient has a local sign of disease (*red*). **b** A digital twin of this patient is constructed in unlimited copies, based on computational network models of thousands of disease-relevant variables. **c** Each twin is computationally treated with one or more of the thousands of drugs. This results in digital cure of one patient (*green*). **d** The drug that has the best effect on the digital twin is selected for treatment of the patient

Fig. 2 Digital twin concept for personalized medicine [13]

However, the fact that the human organism is more complex than any other artificial device and system poses scientific and technical challenges, which must be overcome for implementation. To do this, it is necessary to understand the mechanisms of some basic issues, such as (1) the biological and homeostatic mechanisms required for us to maintain good health, (2) the ever-evolving data capturing different determinants of our health, from genomic sequences to behavioral data, (3) the technologies to enable this cooperation, and (4) the growing cooperation between clinical and engineering sciences.

The use of the DT provides scientists, healthcare providers, and hospitals with the ability to simulate environments specific to their requirements, whether in real-time or for future developments and usage. Additionally, DT can make smarter predictions and decisions by using it simultaneously with AI algorithms [2]. It can also be used in many areas, such as hospital management and determining empty beds.

Ross et al. presented their study with Hewlett-Packard by using AI and IoT to create visual Digital Twin Avatars of humans. From a healthcare viewpoint, SR technology can be used along with AI algorithms to see the effects of certain lifestyle changes (e.g., exercise and diet) on the health and appearance of a person and suggest specific changes from AI and SR analysis. Such usage emphasizes the full integration of data from both the physical twin (Human) and the DT (Copy). It both gives individuals the ability to see what effect their actions will have on the physical twin and shows the effects of certain lifestyle changes [19].

In the next part, examples of the use of AI, ML, and DTs in various branches of the healthcare system are presented.

2 Internal Medicine

An "artificial pancreas" was developed for patients with type 1 diabetes. This device, which resembles a smartphone, is based on the principle of measuring blood sugar instantly with its sensors, calculating the required insulin dose, and injecting it with the help of a pump. Proper blood glucose level is achieved by calibrating the glucose metabolism with mathematical modeling. In this way, it was stated that the quality of life of patients increases, and the emergency department admissions because of excessive insulin doses decrease [20].

In order for predictive alerts to be effective, they should alert clinicians before significant clinical deterioration occurs in patients. To do this, the flowing features must be present in them: (i) presenting actionable concepts about preventable conditions; (ii) being customizable for specific patients; (iii) providing adequate data to inform clinical decision-making; and (iv) being applicable among patient populations. In this respect, a model was employed to determine kidney damage by using the "deep learning" method; and a large and longitudinal electronic health record dataset was developed covering various clinical settings and consisting of a total of 703.782 adult patients, 172 of whom were inpatients and 1.062 outpatients. This application could predict 55.8% of all hospitalized acute kidney injury episodes and 90.2% of all acute kidney injuries, which required hemodialysis. This is an example of the preventive scanning algorithm methods [21].

3 Surgery

The use of DT in the surgical field may bring benefits such as the trial of the surgical procedure on the simulator before a scheduled surgical procedure, reviewing the anatomical differences and minimizing unwanted damages. It can also be used in surgical training and to apply new medical instruments, new surgical techniques, and treatments without causing any risk to patients [22].

Remote surgery implementations are another exciting area of study. For example, the ability of a surgeon to perform preoperative checkups remotely with a DT can be used to minimize vital risks [2]. An example of such a use in surgical interventions is the model that is employed in brain aneurysm operations. A 3D rotational DT of each patient is created in this model to show the aneurysm and surrounding vessels. In this way, it was reported that it is possible to perform simulations with many implants to help surgeons choose the optimal implant in a shorter time and to understand the interaction between implant and aneurysm [23].

4 Intensive Care

Critical diseases offer advantages for AI model developers compared to chronic diseases such as the large amounts of quantitative and qualitative data and shorter time needed for the transition from a critical condition to a clinically stable state. This made it possible to conduct various simulation studies on different groups of patients. For instance, a group of clinicians and computer scientists from the UK used an AI approach to develop a decision support system that was called the "AI Clinician" [24], which was designed to assist real-time ideal therapeutic interventions for sepsis by using Reinforcement Learning (RL). e-ICU research and MIMIC-III databases were used for validation [25, 26]. With the help of this model, it was found that mortality was at the lowest level in patients for whom the intravenous fluid and vasopressor doses of clinicians matched AI decisions, and it was reported that patient outcomes could be improved with personalized and clinically interpretable treatment decisions regarding sepsis. Tools developed based on existing AI models have low levels of specificity in predicting intervention points for real-life sepsis patients. This is one of the biggest disadvantages of AI models while treating critically ill patients. Although most of the models designed at present time are based on retrospective data from databases, the performance and accuracy of such algorithms may not reach the same level on real-time data. Concerns regarding patient privacy and liability may prevent AI models from being integrated for implementing in daily ICU implementations. Patients are highly heterogeneous and have specific treatment needs, which can easily be demonstrated in mechanically ventilated patients. For example, "Smart Ventilation Modes" may be more harmful to the patient in the absence of the supervision of a specialist physician [1]. However, it was shown that it may be possible to develop and test a causal AI model prospectively for predicting the treatment response in early stages of critical diseases. The availability of quantitative and qualitative data and a short feedback time make the ICU an optimal setting for developing and testing DT models. Furthermore, the correct DT model will allow the effects of an intervention to be tested in a virtual medium before it is employed in real patients [27]. In a complex intensive care setting, clinicians find it challenging to make decisions involving high-degree uncertainty. Although data-based relational AI models promise improved prognosis and diagnostic process, they still have not yet been proven useful in bedside clinical follow-up so far. Creating actionable AI models is more complicated and requires clear consideration of causative mechanisms. Accurately predicting the response to treatment or intervention without exposing patients to potential risks is a process that can be beneficial for both patients and clinicians [1]. In a study by Teo et al. to investigate the quality and duration of sleep through wearable devices and the effects on cardiovascular and biological aging, sleep duration and sleep efficiency data from the wearable device were associated with cardiovascular risk factors such as waist circumference and Body Mass Index, and insufficient sleep was associated with early telomere damage. However, no correlation was detected between the individual feedback data and the results [28].

5 Radiology

The study by Ardila et al. can be given as an example of the use of these technologies in the Radiology and Oncology fields. The researchers used a deep learning algorithm predicting cancer based on patients' instantaneous and the previously taken thoracic Computed Tomography (CT) findings to find solutions to the evaluation differences, false positive–negative results in lung cancer screening. In this respect, the system was found to be very successful in 6.716 patients who were included in the National Lung Cancer Screening Study (Area Under the Curve was 94.4%) and exhibited a performance that was similar to the independent clinical validation set of 1.139 cases. In the absence of prior CT imaging data, the system outperformed six radiologists with reduction of false positivity by 11% and false negativities by 5%. Its performance was at the same level with the same six radiologists when prior CT imaging data were available. The authors reported that this system had the potential to be implemented in lung screening worldwide and stated that it yielded accurate and consistent results [29]. Another example in the radiology field is lung X-ray imaging, which is among the most frequently used examination modalities in daily practice, for diagnosing pneumonia. It was found that this neural network-based algorithm was more successful (76% accuracy) than four radiologists [30]. However, radiologists still have the additional benefit of being able to detect other pathologies during this examination and diagnosing pneumonia, and therefore, current findings must be compared with a larger number of radiologists. In a study that was conducted in India, where deep learning algorithms are used at present time, it was found that the system was at least as successful as radiologists in evaluating four different findings in lung X-ray imaging [31]. A total of 37.000 3D cranial CT scans were analyzed with deep learning algorithms examining 13 different anatomical regions determined by radiologists to determine the prevalence of acute neurological events such as stroke and head traumas. The simulation that was created for this purpose was tested on real cases in a randomized, double-blind, prospective study, and it was found as a result that the system could analyze 150 times faster than radiologists (1.2 vs 177 s); however, the diagnostic accuracy was lower [32]. Besides these, smart digital technologies have many other uses in the field of radiology, bone X-rays for fractures and age determination, tuberculosis classification, vertebral compression fractures, CT for liver masses, lung nodules, pancreatic cancer, coronary calcium scores, cranial images for bleeding, head traumas, ECGs, and mammography. It was found that the diagnostic accuracy rates of these samples were approximately 56–99%. Here, the point that must not be remembered is that such algorithms cannot be trusted unless they are tested in real-life situations [18]. In radiology, Artificial Intelligence implementations have many uses other than diagnostic purposes. The first among these is the X-ray stage. It was reported that the shooting time can be shortened with its use at this stage, human errors can be reduced, and better imaging results can be obtained by reducing operator dependence. Secondly, studies on the use of this in the reporting stage continue, and in this area, it will be possible to detect and define errors automatically in the images and make the necessary measurements. Thirdly, it will be possible to use it on a patient basis by integrating the clinical data of patients. The AI algorithms at this level will serve to predict specific patterns in images beyond mere measurement and identification. AI-based prediction can be in the form of predicting disease progression, risk stratification, or determining the outcome of certain treatments applied. Finally, at the fourth level, AI implementations on data incorporated at the population or cohort level can be discussed. Such data and related outcomes will become increasingly accessible with the continuing trend of consolidation in healthcare systems, especially in large institutions, which will bring the use of AI algorithms into question not only in overcoming clinical decision-making challenges but also in operational decisions resulting in efficiency and adherence to guidelines, protocols, and quality measures [33]. Failure to position the patient appropriately may result in- or over-dosage in the anatomically adjusted dosing stage. Positive results have been reported on AI-based positioning in this regard. This was achieved by an AI-based algorithm that automatically analyzes the patient's body shape from the data of a 3D depth camera placed on the patient and creates a patient-specific 3D avatar (i.e., body surface and contour). Using 3D camera data without AI-based avatar modeling cannot show the same success because the patient can be covered with blankets or s/he might lie on cushions, etc. Such AI systems can not only reduce errors because of operator dependency and standardization but also reduce exposure times and radiation doses through automatic table height and scan detection [34]. MyExam Companion (Siemens Healthcare GmbH, Forchheim, Germany), which is a recently introduced data-based CT scanning automation solution, uses a large set of patient characteristics' training datasets derived from decision trees and corresponding scanning protocols across clinical institutions. In this way, it eliminates the technical complexity and the risk of user errors, ensuring standardized image quality with specific and regional preferences for the area to be examined [33]. Among the other uses of AI in radiology, there are the visualizing of the images retaken to make it easy for the radiologist to interpret, multi-layered reorganization of CT examinations of the heart, coronary arteries, and carotid arteries (i.e., curved multiplanar reformations), detection of rib fractures with high sensitivity, detecting acute situations such as cerebral hemorrhage aortic dissection, pulmonary embolism, triage, and alerting the clinician and radiologist [33]. A machine learning-based algorithm for calculating fractional flow reserve in CT Angiography (CTA) images is reported in a cardiovascular implementation based on Digital Twin modeling. In this study, an AI algorithm was trained on a large database of synthetically generated coronary anatomical structures and corresponding flows and reported that this AI algorithm can learn hemodynamics without time-consuming and expensive computational fluid dynamics simulations [35]. This method was evaluated clinically in a multicenter study conducted with 351 patients. In this respect, CT-Fractional Flow Reserve (CT-FFR) based on Machine Learning (ML) and used with Computerized Flow Dynamics

(CFD) is performed better than CT Angiography (CTA). The diagnostic accuracy increased in each vessel from 58 to 78% with CTA and ML-based CT-FFR, and the accuracy increased for each patient from 71 to 85% with CTA when ML-based CT-FFR was added. The false positive CTA result, which was detected in 62 (73%) of 85 patients, was classified again correctly with ML-based CT-FFR. The results were validated with reference to the invasive method [36].

6 Geriatrics

An example of an application to prevent diseases can be given to the elderly. In this context, a real-time monitoring and alarm system based on the DT technology has been developed in China. The system collects information on the posture and behavior of the person with the implementation of a visual sensor, an Artificial Intelligence chip, and deep learning technology. After the calculation and analysis made by the Artificial Intelligence chip, it presents these data in the cloud with digital mapping. When the safety threshold is exceeded, the alarm can be activated to prevent or mitigate the injury caused by the fall of the elderly. The user can set alarm thresholds in different time zones and areas and achieve the purpose of the product determined before [37]. An example of implementation in the elderly is related to the use of DT in nurseries. It is predicted that the elderly in nurseries will be provided with tools that will increase their safety, optimize the results of physical and cognitive treatments, and provide a more independent and higher-quality living environment by providing solutions for a healthy lifestyle [38].

7 Chest Diseases

In a study that evaluated the time and place of inhaler use with electronic sensors in asthma patients, it was found that there was a 78% decrease in emergency inhaler use and a 48% increase in the number of symptom-free days with this method. It was also found to help make recommendations for environmental changes to be applied to reduce asthma symptoms [39].

8 Pathology

A faster and more accurate opportunity can be achieved by digitizing the pathology preparations and examining these data based on Artificial Intelligence. When the pathologist and Artificial Intelligence algorithms were compared in breast cancer cases, no differences were detected if there was no time limit; however, it was also found that the algorithms were more successful when a time limit of 1 min was set for each slide. However, this is not a viable approach regarding real-life workflow [40]. Also, instead of comparing Artificial Intelligence and pathologists, there are cooperative models. In this way, it was possible to make the most accurate diagnosis in the shortest time [41]. The first prospective study testing the accuracy of an algorithm for classifying digital pathology slides in a real clinical setting was conducted by comparing deep learning algorithms with six pathologists for breast cancer micrometastases in the slides. Only one false positivity and two false negativities were obtained, resulting in more than 90% diagnostic success. This system is also not affected by poor staining, over-fixation, and air bubbles of the preparation that cause histological artifacts [42].

9 Dermatology

Artificial Intelligence-based algorithms that were prepared using many pictures and dermoscopy images, generally in diagnosing cancers such as melanoma and carcinoma, were compared with dermatology experts in studies that were conducted in the field of dermatology. Because of these studies, which were not conducted on patients, the system achieved more successful results than physicians, with a rate of more than 95%. Successful results have also been reported in the diagnosis of other dermatological diseases. However, real-life data are needed on this topic [43–45].

10 Eye Diseases

After AI-based algorithms were compared with ophthalmologists and 10.000 fundus images of 5.000 patients were examined, it was found that the algorithm could diagnose diabetic retinopathy with 90% sensitivity and 98% specificity [46]. An accurate diagnosis could be made between 88 and 92% with the algorithm that evaluates retinal fundus images used to detect macular degeneration related to age [47]. Again, after the evaluation of the retinal Optic Coherence Tomography (OCT) imaging to identify diseases such as age-related macular degeneration and diabetic retinopathy, which are among the most common causes of vision loss, and compared with an ophthalmologist, the accuracy rate was found to be 99.9% for emergency admission [18]. A total of 900 patients who had diabetes but not any known retinopathy were evaluated using a proprietary system that acquired retinal fundus photographs and OCT and by reading centers that had the expertise in interpreting these images in a prospective study that was conducted in primary care clinics. The algorithm was used in primary care clinics and achieved a sensitivity of 87% and specificity of 91% for 819 patients who had analyzable images. Finally, the algorithm achieved FDA approval for the autonomous detection of "*more than mild*" diabetic retinopathy without the need for a clinician [48, 49]. Studies are underway for the diagnosis of congenital cataracts in the eye area and retinopathy in premature newborns.

11 Cardiology

The two most commonly used diagnostic methods are Electrocardiography (ECG) and Echocardiography (ECHO) in the field of cardiology. The usability of both methods has been tested with deep learning algorithms for a long time. In a study using a retrospective dataset of 549 ECGs, sensitivity of 93% and a specificity of 90% were obtained compared with cardiologists with deep learning algorithms for diagnosing heart attack. [50]. Again, in a study in which more than 64,000 single-electrode ECGs of more than 29,000 patients were evaluated for arrhythmia with an algorithm and board-certified cardiologist and in which 14 different electrical conduction disorders were examined, the algorithm yielded very successful results. With the help of this algorithm, it is considered that it can be used for diagnostic purposes when combined with inexpensive ECG devices to prevent erroneous evaluations, reduce the time loss to cardiologists, and in healthcare centers that have difficulty in accessing cardiologists [51]. A deep learning algorithm and cardiologists evaluated a dataset consisting of more than 830,000 still images in a study of 267 patients regarding echocardiography. The overall accuracy for single still images was found to be 92% for the algorithm and 79% for cardiologists. However, it was reported that this result may not be reliable in reflecting real life because it was obtained using still images and the ECO process was performed using moving images [52]. Ventricular Assist Devices (VADs) must be developed because of the increase in the number of patients and the lack of sufficient donors to meet the requirement for heart transplantation in end-stage congestive heart failure patients. For this purpose, a new extravascular VAD technology was developed to provide biventricular and epicardial pressure support for the heart. This new concept also prevents blood contact, which causes complications such as clotting and infections. In this concept, a personalized functional DT of the heart, vascular system, and new VAD technology was created with a calibrated and customized computational model. It was reported in previous studies that this model can (a) validate in vivo experimental data, (b) predict healthy and pathological ventricular function, and (c) evaluate the benefits of the new VAD concept. The model fits very well with in vivo data and predicts increases in stroke volume and left ventricular pressure with increased ventricular support reliably. DT also provides information about the insufficient data or impossible to measure in any experimental study. This model is deemed as an important tool for future treatment modalities for treating heart failure [53]. In a randomized, controlled, and prospective study that was conducted in Germany, web-based remote treatment and standard treatment were compared in heart failure patients. As a result, decreases were detected in unplanned cardiovascular admissions to hospital (p: 0.046) and all-cause mortality rates (p: 0.028) with remote patient management. No significant differences were detected in mortality rates because of cardiovascular reasons [54]. It is predicted that such implementations will take an important place in the future. They can be used to treat patients as well as to prevent them from being ill. DT implementations can be used not only for the whole human body but also for some specific organs and tissues. For example, Siemens Healthineers transferred the electrical and physical features and structure of the heart to a 3D image with an AI-based DT model by using the data collected in a database of more than 250 million images and reports. This method was tested for 6 years in the Digital Twins of 100 patients who were treated for heart failure. It was found that the preliminary results of the comparisons between the actual results and the predictions that were made by the computer after analyzing the DTs were positive. A pilot scheme, which was called "Cardiac Resynchronization Treatment (CRT)," is underway to identify patients who may benefit from this treatment early and to administer treatment more individually [10, 55]. Pulsatile blood flow causes a slight head movement in the carotid arteries, which is presumed to be a potential indicator of the severity of carotid artery stenosis. To detect this, an algorithm was created which determined different degrees of occlusion with many head movements virtually by using a computerized visual algorithm with in vivo videos of the human face. In this respect, in vivo vibrations were compared with virtual vibration data that were generated from the computational blood flow/vibration model. Preliminary results in healthy subjects and one patient showed that the model was accurate and had the potential to detect the severity of carotid artery stenosis [14].

12 Gastroenterology

With colonoscopy, it can be extremely difficult for gastroenterologists to find small (< 5 mm) sessile or adenomatous polyps. In a prospective study, Artificial Intelligence was used in routine colonoscopy in 325 patients who had 466 small polyps, and accuracy of 94% and a negative predictive value of 96% were reported. The diagnostic speed was found to be 35 s with Artificial Intelligence, and the algorithm provided similar results with new and experienced gastroenterologists without the need for use of staining [56, 57].

13 Psychiatry

One of the most common mental illnesses in the world is depression. Various studies have been conducted to diagnose, monitor, and treat depression. Keyboard interactions, voice–face recognition, various sensors, chats through interactive bots, which will be implemented through Artificial Intelligence, can be used for these purposes. It has been reported that depression can be predicted through social media posts. There are studies predicting the success of depression treatment and predicting suicidality and attacks in patients with schizophrenia with machine learning [18].

14 Infection Epidemiology

A simulation study was conducted on the current COVID-19 pandemic to evaluate the short- and long-term effects of the pandemics on the supply chain. In this respect, it was determined that the most important parameter that affected the supply chain during the pandemic was the timing of closing–opening of the facilities at different stages. Besides, supply time, the rate of spread of the pandemic, and upstream–downstream interruptions in the supply chain were listed among other important factors. The risks that might occur in preparing pandemic plans can be prevented or reduced by using such models [58]. One of the most important hospital-acquired infections is *Clostridium difficile*-related infections. It was reported that approximately 300,000 infections cause an annual scale in the USA. Early identification and treatment of people who are at risk of these infections are critical. For this purpose, a model was created by compiling the electronic records of adult patients admitted to two large hospitals. In this respect, it was found that the patients who were at risk could be detected at a rate of 82% and 75%, respectively, with the method used. It was also determined that this method could be applied to other hospitals or specifically to one hospital if desired, so that people who are at risk of such an infection can be detected more accurately and earlier [59]. A model that included the complaints of patients at admission, nurse observations, and vital signs was found to be successful for diagnosing infection in the emergency department [60]. Sepsis is one of the most important mortality reasons. It is extremely important to diagnose and treat sepsis earlier so that morbidity and mortality rates can decrease. Henry et al. developed an early warning system, which was called "TREWScore" for septic shock, based on the existing recorded data and monitoring records of patients. With this system, it was possible to make a diagnosis with 67% specificity and 85% sensitivity before the development of major damage because of sepsis (median 28.2 h before). Two-thirds of the patients were diagnosed before the organ damage had occurred [61]. Another system that used electronic health records, which could provide 24 h of notice before the onset of severe sepsis, was also used in this respect [62].

15 Orthopedics

Rehabilitation implementations in spinal cord injury patients can be given as an example of the use of the DT in orthopedics and physical treatment. In this respect, data are collected from patients with the help of EEG, EMG, and sensors, which are evaluated in the DT of the patient, and the optimal muscle and skeletal tension and the amount of mechanical or electrical support needed are calculated and implemented to the supporting device and then to the patient [63]. A schematic representation of this model is given in Fig. 3.

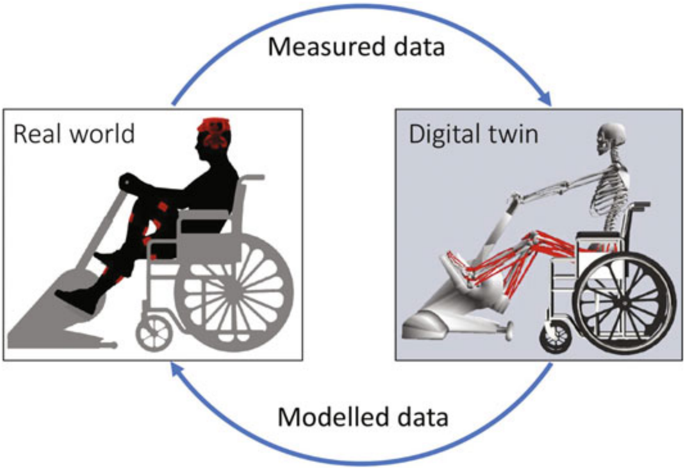

Fig. 3 Schematic representation of the interaction between real-world devices and Digital Twin [63]

16 Neurology

It was reported previously that DT technology can be used in a large amount of accurate data to be collected from patients during the diagnosis (collection of data on the type and stage of the disease, related symptoms, comorbidities, the time between the first presentation to the neurologist and MRI results), follow-up (disease activity markers), and treatment of acute attacks and symptomatic treatment of the long-term and complex diseases such as Multiple Sclerosis (MS). In the treatment decision, the purpose will be to select the most appropriate drug for the individual considering his/her medical history, the stage of the disease, the degree of disability, initial symptoms, age, gender, child desire, and comorbidities. It will also be possible to monitor possible drug reactions and side effects [10]. In a study that was based on predicting the efficacy of various treatments in relapsing MS attacks, it was determined that this method made strong and accurate predictions and could be generalized to new patients [64]. In another similar study, the purpose was to predict six different clinical responses of seven different treatments based on the demographic, clinical, and paraclinical data of patients. At the end of the study, it was successfully predicted which factors and treatments could increase/decrease physical disability and disease recurrence [65].

17 Barriers to the Use of DTs in Healthcare Systems

Although DTs have many benefits in the healthcare system, such as prevention, prognosis, and treatment selection, and increasing the quality of patient care, there are also some challenges and hesitations about their use. For example, missing or incorrect data may result in incorrect modeling and recommendations. It has great importance that these data are high quality and are standardized and reliable so that DTs are not separated from their true twins and can be fully represented [2, 66]. The presence of data in digital media rather than paper media is important in terms of accelerating data flow and data analysis.

18 Data Privacy

Before a DT is created, it must be determined who can access the data, for how long, for what purpose, and under which conditions. To do this, it is necessary to make appropriate regulations by the state authority. Efforts must be made to protect the data against hacker attacks and to prevent data losses, which may cause damage to patients, who, in such a case, must also ensure that their data are kept secure, transparent, and accessible to them. Or else, collecting patient data may increase distrust rather than trust in healthcare systems. It is inadequate merely to provide technological advances, and it is also necessary to ensure that such technological advances serve to improve the well-being of patients. For this reason, data privacy and transparency in data use must be respected with the full consent of the patients. Informed consent forms must be obtained, and the purpose of the data collection must be clearly stated to patients [10].

19 Ethical Issues

It has been argued that DT may cause inequality in the healthcare system because of the possibility of underrepresentation of some racial or patient groups. If a group is underrepresented in an established model, it is likely that such a group will receive suboptimal treatment [67]. For example, patients who have a history of asthma and pneumonia were classified in a computer model as patients who had a lower risk of mortality than those diagnosed with pneumonia alone. When this condition was evaluated, it was found to be because of the earlier and more aggressive treatment of asthma patients by clinicians [68].

Another crucial ethical issue about predicting the course of a disease is how the prognosis will be communicated to a patient. How does a patient cope with the information that they will soon be in a wheelchair as the medical prediction says? Do patients have the right to "*not to know*" about their disease? Can patients decide on a treatment that will be good or bad for them based on the results at hand? For this reason, patients must develop an appropriate relationship with their personal DT and can make informed decisions with data-based personalized models [9].

20 Human Factors and Other Issues

The importance of AI users must not be overlooked. Trust is one of the most important factors in such new implementations. Clinicians who do not know enough about algorithms and AI implementations may not have adequate confidence in the results and treatment recommendations. Also, there are concerns that the use of Artificial Intelligence in the healthcare system may cause unemployment or disqualification of healthcare employees. For one thing, automated blood pressure measurement and automated blood cell counts eliminate the requirement for healthcare staff to perform these tasks. However, there is a key function of physicians in patient care, such as the role of "*god physician*" in the historical process. Therefore, physicians must proactively guide, supervise, and monitor the adoption of AI as a partner in patient care. When collaborates with Artificial Intelligence, human intelligence can save valuable time by being a well-informed, empathetic clinician, who is armed with good predictive tools, and is freed from the burden of clerical work. In this way, such a clinician will have the opportunity to work more efficiently [69, 70]. AI-based decisions will assist the clinician in making accurate decisions, providing that they keep human intelligence up-to-date and consider social, clinical, and personal characteristics [69]. If DT recommendations conflict with clinician recommendations, the clinician must develop a new action plan to make an accurate decision, or else, more data may add to the uncertainty of medical considerations [10]. It must not be ignored that the results obtained by DT can be complex and, therefore, complicate the patient follow-up. For this reason, it must be considered which data contribute at the highest level to predictability, how this predictability can be used, and how this method can be applied and incorporated into the healthcare system in a cost-effective manner. It is considered that the large amount of data at hand will bring benefits such as providing accurate and fast information to clinicians in the field of health care, improving workflow for healthcare systems, reducing medical errors, and improving the health status of patients by obtaining their own data with the help of advanced computer technology and cloud systems. Today, some limitations of such implementations are bias, personal security and privacy, and data transparency [18]. Despite all above-mentioned difficulties, there are countries such as Estonia, which have been able to successfully implement the concept of DT. To achieve this, efforts must be made to establish guidelines, gold standards, benchmarks, and government legislation [12, 18]. Studies must be published in peer-reviewed journals, and this must be validated clinically in real life before using DTs in patient care.

21 Conclusion

Although the use of computer-based technologies such as DTs and AI in health is new, it offers great hope for the future. It is expected to provide benefits such as diagnosis, medical and surgical treatment, protecting and improving the health status of people, and predicting the health problems. In this chapter, examples of its use in different fields of medicine are given and it is expected that these will increase over time. In order for the Digital Twin to fully represent the real twin, it is of great importance that the data are of high quality, standardized, and reliable. Therefore, it is necessary to develop appropriate data collection tools. The complexity of the human organism, genetic, environmental and mental factors are other problems that need to be considered. Finally, it is extremely important to establish legal regulations and ensure data security.

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Digital Twin in Chronic Wound Management

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1 Introduction

Wound management has been studied for many years since its healing requires dedicated care [1]. The economic burden of wound care in the USA reached US$25 billion yearly with an increasing trend [2]. Even spending on wound care products outstretches to US$30 billion per year [3]. Wound care gets the highest share among any other skin diseases [4]. Wounds can be classified into two groups; the first is acute wounds, which follow an orderly healing process, whereas the second group, chronic wounds, does not progress in an orderly manner. One of the recent studies

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_11

indicates that mortality rates from chronic wounds are also on par with cancer for some patients [5]. That's why proper and continuous care is critical for hard-to-heal or non-healing wounds.

Wounds or injuries result from disruptions in the normal architecture of any body tissue, especially on the skin [6]. Wounds are historically examined through visual inspection, which is still broadly in use today. Advanced image processing and artificial intelligence (AI) techniques enormously contribute to the diagnosis and management of chronic wounds [7, 8]. Recent studies use deep learning methods on images with transfer learning techniques to distinguish different wound types [9–11]. Taking advantage of previously learned features enhances the performances of models with small datasets. Other AI techniques are also used to segment wound images to analyze the distribution of wound tissues [12–16], where tissue distribution provides essential information about the healing status of the wounds. Wound assessment is also investigated using machine learning techniques to measure the physical dimensions of hard-to-heal wounds [17, 18].

Besides diagnosis and management, prognosis and decision support systems for chronic wounds could be developed using AI and the recently adopted digital twin (DT) concept in healthcare [19]. Digital twins are essentially virtual replications of physical objects and processes. They use the Internet of Things (IoT), artificial intelligence, and complex data in models that create insights and support (real-time) decision making. It is perhaps healthcare that holds the greatest potential for Digital Twins. Healing chronic wounds take weeks, maybe months which requires periodical examinations and continuing care. DT application in wound care is feasible as longer and slower healing pace of hard-to-heal wounds will provide flexibility to handle surfacing health conditions. In this paper, chronic wounds and the digital twin concept are examined to develop a framework for DT for chronic wound management. Contributions of this study two folds: (1) investigation of chronic wounds and DT technologies, (2) development of DT for chronic wound management.

The remaining sections of this paper are organized as follows. Exploration of digital twin use in healthcare with implementations and proposals is provided in Sect. 2. Section 3 provides a review of current chronic wounds and underlying tissues as well as treatment methods, followed by enabling technologies to further understand the application of the digital twin concept on chronic wounds. A general chronic wound management framework using the digital twin is investigated in Sect. 4. Section 5 provides details about the methodology and the implementation of the proposed image-based digital twin model. Results, opportunities, and challenges are discussed in Sect. 6. The paper is concluded with Sect. 7.

2 Digital Twin in Healthcare

The digital twin concept in healthcare is still in its infancy due to privacy concerns and the vulnerable nature of healthcare. The security aspect of DT usage in healthcare is studied by the authors in [20]. Blockchain-based secure DT framework is proposed, and a case study covering the recent COVID-19 pandemic is discussed to provide security of the shared data. Another study that emphasizes vulnerability detection for cyber resilience in healthcare digital twins is explored by the authors in [21]. One of the prior works proposes cloud-based digital twin healthcare (Cloud-DTH) for elderly patients [22]. The cloud-based healthcare service platform is proposed for real-time monitoring, crisis warning, medication reminder, and disease diagnosis. One of the case studies utilized DT is proposed for an electrocardiogram classification framework to diagnose heart disease and detect heart problems using machine learning techniques [23]. An ischemic heart disease (IHD) recognition DT architecture is also proposed by the authors in [24]. The presented DT model works on the edge and utilizes convolutional neural networks (CNN) to classify myocardial conditions with an accuracy of 85.77%. Authors in [25] integrate DT with multi-agent systems as mirror worlds in a case study. This case study digitalizes to support the process of trauma management. An augmented DT is proposed to lay the foundations of the full life cycle DT of a human being [26]. In addition to these, the potential of the digital twin technology in health is reviewed by Erol et al. [27].

These studies indicate that the utilization of the DT concept has great potential. More case studies should be done to unleash this potential since the needed technology is available. To overcome privacy and security issues in DT, new methods and technologies should be adopted as well.

3 Review of Chronic Wound Management

Chronic wound management requires special care in order to heal [1]. Treatments and the lengthy healing course are tracked with long-established visual methods. This section examines the tissue types, treatment methods, and evaluation metrics for building digital twins.

3.1 Types of Wounds and Tissues

There have been various diseases and incidents that could harm and break the integrity of the skin. Wounds could be classified into two groups regarding their healing process, i.e., acute and chronic. Acute wounds follow an orderly path during the healing and tend to heal in a short period of time. Whereas chronic wounds distinguish by their complicated and challenging healing process. These kinds of wounds are also called hard-to-heal wounds. Along with hardship in healing, some of them could pose serious risks like loss of limbs and mortality.

Some hard-to-heal wounds are pressure injury, burn, venous, diabetic, and surgical. Pressure injury wounds are caused by stress or force on the surface of the skin, which are the result of limited mobility. Prolonged inpatient stays and lack of movement at hospitals also pose a greater risk of pressure ulcer [28, 29]. Diabetes is one of the largest epidemics in this century, and around half a billion people suffer from it [30]. One of the complications of diabetes is nerve damage and neuropathy [31]. Studies showed that patients with diabetes have around a 20% risk of developing an ulcer that costs more than US$10 billion in the USA [32, 33]. Vascular or arterial wounds, another major wound type, are caused by poor blood flow below the knee, which can affect both legs. A similar wound type, venous ulcers, is developed as a result of damaged veins from high blood pressure [34]. Both wounds share similar characteristics, but different approaches are required to cure them. Burn wounds are also very common and caused by heat which damages the tissues and underlying structure of the body [35]. These are some of the notable wound types.

The wound tissues are tracked for centuries as visual inspection of the wounds plays utmost importance to determine the status of the wounds. There is a red-yellow-black (RYB) tissue classification methodology that was introduced by Cuzzell in 1988 [36]. This tissue classification provided a simpler and universally accepted system that red areas can be granulated, yellow areas can be slough, and black areas contain eschar (necrotic) tissue [37]. Eschar (Black) and slough (Yellow) are tissues, not ready to heal. These tissues will be removed to accumulate a swift healing process.

3.2 Continuum of Wound Healing

After the incident, injury breaks the blood circulation and causes bleeding. Granulation tissue (Red tissue) plays an important role in healing. There are four phases for the healing of wounds. The hemostasis phase is the first step of healing. In this phase, the wound is sealed with various molecular binding agents. The inflammatory phase will cause swelling due to the production of a transudate. With this phase, infections are prevented. The proliferative phase will form new tissues and blood vessels to circulate enough oxygen and nutrients. The remodeling or maturation phase will provide the required materials so as to heal a wound completely. These phases follow a planned healing procedure that chronic wounds do not follow any order.

3.3 Treatment Methods and Evaluation

The healing endeavor has been discussed and practiced for many centuries since wounds are easily recognized visually, and their track depends on visual assessment in the first place. Cleansing the wound and removal of the dead tissue, also called debridement, is critical in some cases. After the application of debridement, ready-to-heal tissues emerge, and healing is sped up with the living tissue. Ultrasound, laser surgery, or irrigation are some debridement methods used in current wound management. Another essential method to treat and heal wounds is dressing, which could be dry or wet [38].

Each wound type has its own characteristics and requires distinct treatment methods. Pressure injury wounds are treated using various dressing hydrogels (water-based gels), hydrocolloid dressing, and foam dressings. Diabetic ulcers are treated with a silver ion foam dressing. Besides this, this type of wound care requires a care team to manage the wound appropriately. Improving blood circulation is one of the essential methods to cure arterial or vascular wounds. Compression stockings could be used to prevent blood pressure to cure venous ulcers. Burn wounds could benefit from dressings as well, severe burns could require skin grafting from other healthy parts of the body,

Various ointments and dressings could be used to fight infection, as well as oral medicines. The aforementioned techniques are some of the traditional treatment methods used to cure wounds. There are also dressing-free therapies, skin grafting, and 3D bioprinting techniques. Emerging therapy solutions are investigated and proposed continuously to improve the healing procedures and patients' quality of life.

Evaluation of the wounds is carried out by surface area measurement, which is a simple and least expensive method. Previously utilized methods are rulers mathematical models, manual planimetry, digital planimetry, stereophotogrammetry, and digital imaging [39]. The latter methods have been adopted as it is non-invasive and provide better results. There are also near-infrared methods such as angiography, laser speckle contrast imaging, and optical coherence tomography [40].

4 Enabling Technologies

4.1 High-Performance Computing

High-performance computing (HPC) is essential for developing the digital twin in healthcare [41]. The digital twin requires efficient data management, processing, and analysis. These tasks are demanding in terms of speed and accuracy. For instance, the digital twin requires a large amount of data to model the patient, which is impossible with a single computer. Therefore, HPC is required to manage and analyze this data. In addition, HPC will help to take advantage of the data collected from various sources, such as electronic health records (EHRs), clinical trials, sensors, and imaging devices [42]. In the healthcare field, HPC can be used to develop new treatments, diagnostic tools, personalized medicine, and clinical trials.

4.2 Internet of Things

Internet of Things (IoT) is a network of physical devices, vehicles, buildings, and other items embedded with electronics, software, sensors, actuators, and connectivity, enabling these objects to connect, collect, and exchange data.

IoT in healthcare can provide many benefits, such as improving patient care, reducing costs, and improving clinical outcomes. In addition, IoT can be used for remote patient monitoring, patient engagement, and disease management. IoT can monitor patients' vital signs and wound healing progress in chronic wound management. For instance, IoT can collect data from sensors placed on the patient's skin to monitor the wound's healing progress. In addition, IoT can be used for remote patient monitoring. For instance, patients with chronic wounds can be monitored remotely using IoT devices. These devices can collect data from patients and send it to healthcare providers. This data can monitor the patient's health and provide the necessary care.

4.3 Artificial Intelligence

Artificial intelligence (AI) is the ability of a computer system to perform tasks that require intelligence. AI can be used for various tasks, such as decision making, pattern recognition, and natural language processing. AI has been used in many fields, such as manufacturing, automotive, and healthcare. AI in healthcare can provide many benefits, such as improving patient care, reducing costs, and improving clinical outcomes [43].

In chronic wound management, AI can be used for various tasks, such as wound classification, segmentation, and healing prediction. AI can be used for wound classification to classify wounds into different categories, such as burns, ulcers, and cuts. AI can also be used for wound segmentation to segment wounds into different parts, such as the edges, center, and surrounding tissue. AI can also be used for wound healing prediction to predict the healing progress of wounds.

4.4 Edge and Fog Computing

Edge computing is a distributed computing paradigm that brings computation and data storage closer to the location needed to improve response times and save bandwidth. Edge computing is used in many applications, such as video streaming, virtual reality, and autonomous vehicles. In healthcare, edge computing can be used for various tasks, such as patient monitoring, disease management, and decision support [44].

4.5 Cloud Computing

Cloud computing is a type of computing that provides computing resources over the Internet. Cloud computing can be used for various tasks, such as storage, data analysis, and machine learning. Cloud computing can be used for multiple tasks in healthcare, such as patient data management, disease management, and clinical decision support. Cloud computing has many benefits, such as scalability, flexibility, and cost-effectiveness.

4.6 Data Privacy Concerns and Privacy Enhanced Techniques for Electronic Health Records

The data generated by chronic wound patients is confidential and must be protected. Data privacy concerns and privacy-enhanced techniques protect the data. In particular, data privacy concerns and privacy-enhanced techniques are used to protect the data in electronic health records. There are two different approaches to protect the privacy of sensitive health records where the first approach is to encrypt the EHRs using homomorphic encryption techniques before storing them in the cloud and the second approach is to use federated learning techniques to train the machine learning models on the EHRs without sharing the EHRs with the central server.

Homomorphic encryption is a type of encryption that allows mathematical operations to be performed on ciphertexts, which results in an encrypted result that, when decrypted, matches the result of the operations as if they had been performed on the plaintext. There are three subcategories of homomorphic encryption: partially homomorphic encryption, somewhat homomorphic encryption, and fully homomorphic encryption. Partially homomorphic encryption algorithms allow mathematical operations to be performed on ciphertexts, which results in an encrypted result that, when decrypted, matches the result of the operations as if they had been performed on the plaintext. However, the number of operations performed on the ciphertext is limited. Somewhat homomorphic encryption algorithms allow an unlimited number of mathematical operations to be performed on ciphertexts. However, the number of operations performed on the ciphertext is limited. The partially homomorphic encryption algorithms such as Paillier, ElGamal, and RSA can be used to encrypt the EHRs before storing them in the cloud. They can be only additive homomorphic or multiplicative homomorphic. The homomorphic property of the Paillier cryptosystem is that it supports the multiplication of ciphertexts while preserving the multiplicative property of the underlying message. That is, if $C_1 = E(M_1)$ and $C_2 = E(M_2)$ are ciphertexts, then the product of the ciphertexts, $C_1 \cdot C_2 = E(M_1 \cdot M_2)$. The homomorphic property of the ElGamal cryptosystem is that it supports the multiplication of ciphertexts while preserving the multiplicative property of the underlying message. That is, if $C_1 = E(M_1)$ and $C_2 = E(M_2)$ are ciphertexts, then the product of the ciphertexts, $C_1 \cdot C_2 = E(M_1 \cdot M_2)$. The homomorphic property of the RSA cryptosystem is that it supports the multiplication of ciphertexts while preserving the multiplicative property of the underlying message. That is, if $C_1 = E(M_1)$ and $C_2 = E(M_2)$ are ciphertexts, then the product of the ciphertexts, $C_1 \cdot C_2 = E(M_1 \cdot M_2)$. Another subcategory in homomorphic encryption is fully homomorphic encryption algorithms. The main drawbacks of fully homomorphic encryption are that it is very slow and not practical for real-world applications. However, it can be used for theoretical purposes. And the last subcategory is somewhat homomorphic encryption algorithms. A limited number of operations can be performed on the ciphertexts. The main advantage of somewhat homomorphic encryption is that it is much faster than fully homomorphic encryption. The main drawback of somewhat homomorphic encryption is that the number of operations performed on the ciphertexts is limited.

The second approach to protecting sensitive EHR privacy is federated learning [45]. Federated learning is a machine learning method that allows multiple devices to train a machine learning model without sharing their data or with a central server. The devices train the machine learning model on their local data and send the model parameters to the central server. The central server then aggregates the model parameters from all the devices and updates the global model. The devices then download the updated global model and continue training the model on their local data. This process is repeated until the global model converges. The main advantage of federated learning is that it allows the machine learning model to be trained on the data of multiple devices without sharing the data or with a central server.

4.7 Blockchain

Distributed ledger technology (DLT) is one of the emerging Industry 4.0 technologies, which was implemented as Bitcoin in 2009. Blockchain technology is a subcategory of DLT and a more popular terminology. Thus, DLT is used manner interchangeably in the industry and academy. DLT is offering new opportunities for the challenging nature of digital twins in healthcare. Collected data in digital twin applications in healthcare require utmost security to eliminate any breach or modification. Corrupted data could bear a high risk for the digital twins as it will lead to wrong decisions [46]. Many functions in digital twins could also be realized using smart contracts. After a triggering event happens, the smart contract could initiate a default behavior [47]. Having secure, immutable, and robust characteristics, DLT enables reliable and automated digital twins. Figure 1 characterizes the use of blockchain in digital twins.

4.8 Communication Networks

As communications technology evolves rapidly from 4G to 5G and beyond networks, a large number of technologies are expected to benefit from these networks in terms

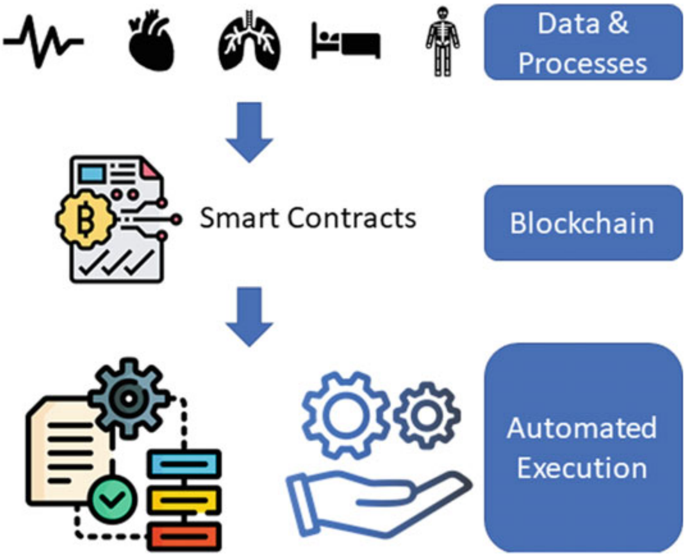

Fig. 1 Blockchain implementation on the digital twin

of high speed, latency, accuracy, and security. The complexity of services such as digital twin is not an incremental increase but an exponential leap. In addition, the implementation of digital twin applications often demands always-on service and near real-time solutions. All these factors pose grand challenges in developing digital twin models utilizing 5G and beyond networks.

To overcome these challenges, advancement in communications is a promising and potential solution that is able to facilitate the data acquisition (DAQ) for digital twins with less complexity, less cost, and more timely. From the collection of data to its storage, network technologies such as Bluetooth, Wi-Fi, NextG, LoRa, 5G, and beyond will be employed for digital twins.

5 Chronic Wound Management System Using Digital Twin

Wounds generally heal between 4 and 6 weeks and show signs of healing within this time frame. However, the chronic wound fails to heal through the normal phases of wound healing in an orderly and timely manner. Although there are many studies and efforts to develop therapeutic ways to effectively treat chronic wounds, it is limited clinical success in chronic wound healing. One of the main reasons is the lack of effective chronic wound management systems or their limitations in terms of technology integration and adaptation [48]. Fortunately, the advanced data communication and computing technologies, along with new concepts, e.g., digital twin, can overcome all these issues and provide a perfect wound management system

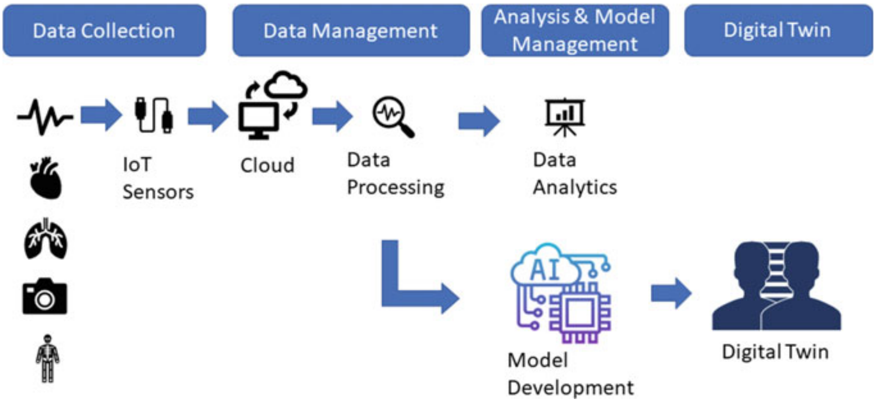

Fig. 2 Proposed system architecture for chronic wound management using the digital twin

beyond expectations. A digital twin is a digital replica of anything from people and processes to systems. A proposed general system architecture is shown in Fig. 2 for chronic wound management using the digital twin. The proposed architecture consists of four main components: data collection, data management, analysis & model management, and digital twin. Each component is briefly explained below.

5.1 Data Collection

The data collection is the starting point of the proposed platform by collecting data from several resources, such as IoT based-devices, i.e., the Internet of Medical Things (IoMT), and healthcare systems. The primary IoMT sensors are pressure, temperature, blood oxygen, image, and flow sensor. This list can be extended as well. IoMT-based devices enable healthcare systems to interact more and connect with the patients. This type of patient care leverages connected devices with IoT sensors to offer providers a continuous stream of real-time health data such as heart rate, blood pressure, and glucose monitoring. Data collected from IoMT devices can also help to find out the best treatment process for patients. IoMT-based applications are also promising in the healthcare sector. These applications include remote patient monitoring, glucose monitoring, heart-rate monitoring, hand hygiene monitoring, depression and mood monitoring, Parkinson's disease monitoring, connected inhalers, ingestible sensors, connected contact lenses, robotic surgery, and many more [49]. In addition to the data collected from IoMT sensors, patient information is crucial in healthcare applications, especially wound management, such as age, gender, smoking, drug, previous condition, chronic wound type, and diabetes.

5.2 Data Management

The second component of the proposed architecture is data management using cloud sources. This component consists of two steps, cloud integration and data processing. Cloud-based systems provide enhanced interoperability and consolidation of the data. Without a uniform data management system, data transmission, processing, and model development tasks suffer from the asynchronous and complex data flow. Cloud services provide real-time data collection and monitoring, which pave the way for the digital twin concept. Without cloud sources, the required infrastructure for data processing and model deployment will cause a burden to many health organizations [22]. Monitoring patients with chronic wounds at home is possible by using cloud services. This will increase the treatment outcomes by providing real-time data. The collected data also needs processing, i.e., data processing, to produce meaningful information for robust analysis and decision and digital twins. This process includes removing or filling in the missing values, detecting outliers, and normalizing the data.

5.3 Analysis and Model Management

The third component of the proposed architecture is the analysis and model management. The proposed architecture offers a prescriptive analytic, where AI and big data combine to help predict outcomes and identify actions to take. In the proposed architecture, the prescriptive analytics allow taking a deeper look into the data and answering "what" and "why" questions for wound data, such as healing stages, and wound size details.

Model management is a sub-component of the proposed architecture. A model should be consistent and accurate in terms of performance metrics. Therefore, a logical, easy-to-follow policy for model management is crucial for the model management. The main purpose of model management is to provide a system for model development, training, versioning, and deployment. It is expected that the models to be developed will be AI-based models. Model management makes it easier to manage the model life cycle from creation, configuration, experimentation, and tracking of the different experiments all the way to model deployment. Under model management, models are also monitored, trained, or retrained with different deployment & deployment strategies. Tracking, comparing, and deploying a model without model management would be very difficult.

5.4 Digital Twin

The last component of the proposed architecture is the digital twin. In wound management systems, digital twins are utilized to build digital representations of those wound data through computer models. Digital twin technology can be used to generate a virtual twin of a wound to review healing stages, size, and type details, to identify the improvement and challenges. Collected tabular data from both sensors and patient information could be utilized for forecasting tasks such as wound closure or healing times. By estimating patient discharge time, used resources could be arranged more effectively. In addition, required treatments or operations could also be forecasted using various information gathered from patients' health history and current status with the help of AI models. In addition, digital twin and its corresponding real-time database can be used to track all necessary data to provide future history of the wound healthcare management plan and provide necessary data for the future decision making. It could also be used for billing purposes, and for further research exploration of what kind of treatment led to improved results. In this way, medical doctors can access this data and make decisions about are surgeries needed or not. Also, they could access the information about the history of previous patients that had similar wound features and what were the future steps in their treatment plan at the time, if they were discharged and when or they needed further medical intervention.

The digital twin in the proposed architecture provides a software-as-a-medical service. The digital twin of wounds is generated from the developed model using collected data. It is also expected that the proposed systems embedded in digital twins can help optimize the software in medical devices as well as caregivers capture and find information shared across physicians and multiple specialists. A proposed image-based digital twin system for chronic wound management is depicted in Fig. 3. Images of the wound are used to construct the digital twin of the chronic wound. The wound image is segmented to understand underlying tissue distribution then a wound healing prediction model forecasts the healing progress of the chronic wound using AI models trained on similar cases. A lifelike wound is generated to visualize the wound itself. The status of the real wound is assessed, and an appropriate treatment method is chosen accordingly.

6 Discussion

The application of the digital twin concept into chronic wound management will ease the overwhelming burden that cumbered the healthcare system. Required continuous clinic visits and care will be reassessed since real-time monitoring, and virtual twin of the wound could detect and flag any imminent health issues. The more digitalized wound care could bring many benefits and challenges as follows:

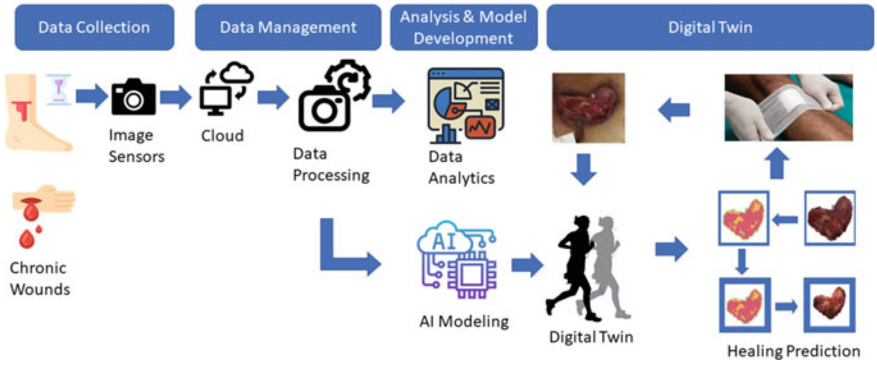

Fig. 3 Proposed framework for chronic wound management using the digital twin

Observation 1: Digital twins can significantly enhance the track and care of wounds by increased monitoring and forecasting capabilities.
Observation 2: Personalized care could be achieved with data-driven approaches that could lead to more efficient and effective care as well as improved outcomes.
Observation 3: Digital twins will provide more information to the patients and encourage them to take more action on their wellbeing.
Observation 4: Digital twins will increase the use of telehealth applications as a result of synchronous track of the wounds. Any medical issue could be detected, and appropriate medical attention could be sought right away.
Observation 5: Newly emerging technologies such as augmented reality and metaverse could be utilized with the digital twin concept.

7 Summary and Conclusion

Chronic wounds or hard-to-heal wounds require special care as their healing course is out of order and takes longer times in comparison with acute wounds. In order to alleviate the heavy cost of constant care and tracking, new technologies should be adopted. The digital twin is one of the key technologies that could lift this burden with improved data management and machine learning techniques.

In this chapter, the adoption of digital twins in healthcare, i.e., chronic wound management, is examined thoroughly to reach optimal treatment and management of wounds. Pieces of the digital twin are reviewed to further increase the opportunities and awareness. Chronic wounds and enabling technologies of the digital twin are explored. A framework for the proposed chronic wound management system is detailed using the digital twin concept. The proposed image-based model gathers images of wounds and processes them to feed into an ML model. ML model then predicts the healed version of the current wound to enhance wound management. In addition to an image-based system, a hybrid model that utilizes both tabular data from IoMT devices and visual data could realize a more comprehensive digital twin formation.

This chapter sheds light on the digital twin concept adaptation into chronic wound management. It is expected that this chapter will provide comprehensive knowledge that can enhance the researchers, engineers, and institutions' vision to reshape their approaches for more efficient and effective wound management systems.

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Digital Twin in Construction

Muhammet Yıldırım and Omer Giran

1 Introduction

On average, the construction sector contributes about 8–10% to the economy of various countries, encourages growth, offers mass employment, and serves as a means of connecting other industries and the economy [19]. The industry drives growth by facilitating services and goods between sectors [7]. The worldwide construction business produced more than $10 trillion in 2017 [10].

Construction is one of the most informative businesses where information needs to be immediate, accurate, thorough, timely, and in a prominent style that the recipient understands [78]. Throughout the life cycle of a construction project, massive amounts of data are generated, from conceptual planning to decommissioning. The ability to manage the flow of information, evaluate the massive amount of data, and derive relevant insights is critical to project success [12].

Although the construction sector is often criticized for being conservative in technological breakthroughs and applications, it has made tremendous strides in improving information management through Building Information Modeling (BIM) in the last few decades [51]. According to Arayici et al. [6], the traditional paradigm of the construction industry has shifted from 2D-based drawings to 3D-based information systems using BIM. BIM has been an effective innovation tool for more than a decade to address building design holistically, strengthen communication and collaboration among key stakeholders, increase productivity, improve overall product quality, reduce fragmentation, and improve efficiency in the construction industry [67, 72].

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_12

While comprehensive research studies have been undertaken to study BIM's use cases and analyze its benefits over the life cycle of a construction project, BIM does not capture data created throughout the operational and usage phase [35]. BIM is faced with substantial issues, with Big Data, Internet of Things (IoT), and Artificial Intelligence (AI) being touted as viable answers to automate and incorporate broader environmental conditions [13]. Thus, in an era of rapid change [11], BIM's evolution ought to be precisely planned within a framework that encompasses all participants and technology [29]. Construction needs to incorporate new technologies as part of the fourth wave of technological innovation (Industry 4.0) [31]. Digital Twin (DT), a digitalization technique used to monitor and improve the operational efficiency of a physical asset by collecting real-time data that enables predictive maintenance and leads to well-informed decision-making, is a crucial component of the Industry 4.0 roadmap [35]. Investments in DTs are expected to balance with increased productivity as a result of predictive analytics [40] or even the supply of value-added services [73]. However, these objectives are frequently not achieved through the collection of data alone but rather through the use of data-driven decision-making [17]. Therefore, this chapter aims to review the use of DTs in construction projects and provide an overview of how to increase their use to improve the quality and productivity of construction projects.

2 The Concept and Origin of DT

Dr. Michael Grieves of the University of Michigan presented what he dubbed the Conceptual Ideal for Product Life Cycle Management (PLM) in 2002, and the notion of DT was born [32]. The PLM idea, which includes all parts of the DT, assumes that each system comprises two systems: a physical system that has always existed and a virtual system that stores all the information linked to the physical system. Since these two systems are interconnected, information can move between the physical and virtual worlds [23]. Other studies have also provided a simplified definition of DT. For example, according to Tao et al. [73], the idea and concept of DT are made up of the physical product, the virtual product, and the connected data that connects the physical and virtual products. The physical space, the virtual space, and the connected data are the three components of the many DT definitions. The twin concept was first used in NASA's Apollo space program. The initiative created two identical spacecrafts so that conditions in space could be mirrored, simulated, and predicted by the vehicle on Earth. The vehicle that stayed on the base was the spacecraft's twin that completed the mission [15]. Hernandez and Hernandez's phrase "DT" was first used in their study [16]. According to Schleich et al. [64], NASA provided the first formal definition of DT in draft version of its technological roadmap in 2010 [59, 68]: "an incorporated multi-physical science, multiscale, the probabilistic reenactment of an as-built vehicle or framework that utilizes the best accessible actual model, sensor refreshes, armada history, and so forth, to reflect the existence of the comparing flying twin."

3 Level of Integration and DT Paradigm

In any situation, one might establish a common understanding of DTs as digital counterparts of physical items based on the above definitions of a DT. The phrases digital model (DM), digital shadow (DS), and DT are frequently used interchangeably in these descriptions. However, the extent of data integration between the physical and digital counterparts differs between the offered descriptions. Some digital representations are created by hand and have no physical connection to the real world, while others are fully linked with real-time data exchange [38]. As a result, the authors propose that DTs can be divided into three subgroups based on their amount of data integration.

A DM is a digital depiction of an existing or projected physical object that does not include any automated data transfer between the physical and digital objects. A more or less detailed description of the physical object could be included in the digital depiction [38]. Suppose there is also an automated one-way data flow between the state of an existing physical object and the state of a digital item. In that case, this combination is referred to as DS, according to the concept of a DM. A change in the physical thing causes a change in the digital item, but not the other way around. It is referred to as a DT if the data flow between an existing physical thing and a digital entity is fully integrated with both directions. The digital item could likewise operate as a controlling instance of the physical thing in this scenario.

Figure 1 shows the data flow, where (a) mentions the data flow in DM, (b) mentions the data flow in DS, and finally, (c) presents the data flow in DT.

The DT paradigm necessitates a more significant level of detail and accuracy from unassuming manufactured resources, buildings, city locale, and ultimately statewide DTs [14]. Grieves [23] proposed a DT method that provided a holistic perspective on the complex system that a DT represents. Therefore, the primary DT units considered here, as illustrated in Fig. 2, are physical components, virtual clones, and data that connect each other.

"Data" in its different forms provide the connection loop between the system's "Virtual-Physical" duality. Such as, Grieves [23] recognizes data from "Physical" to "Virtual" to be raw and in need of processing. In contrast, data from the "Virtual" to the "Physical" are dependent upon a few changes that can be handled data and put away information through digital models—with higher levels of significance. Nevertheless, the data are eventually reflected in the "Physical" via actuators. As a result,

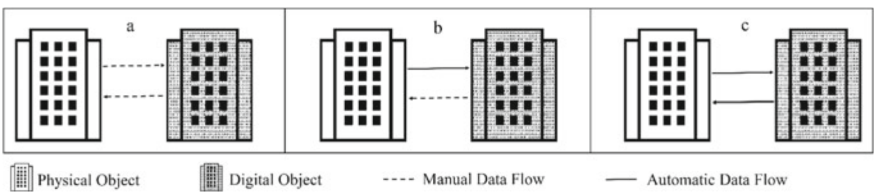

Fig. 1 Data flow in DM, DS, and DT (adapted from: Kritzinger et al. [38])

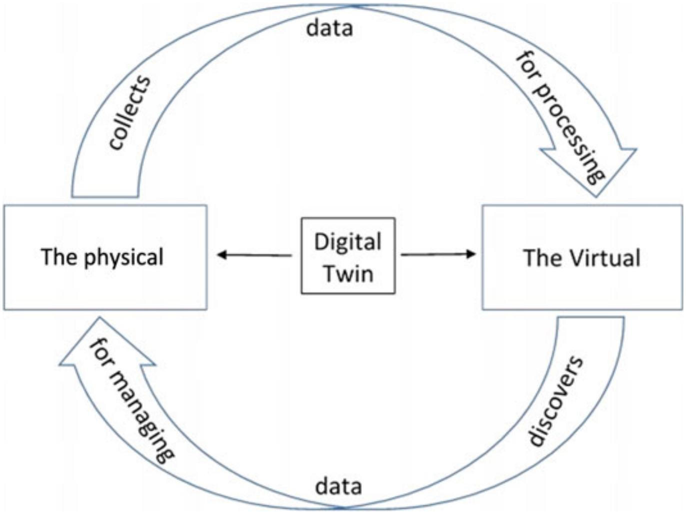

Fig. 2 DT paradigm (adapted from: Boje et al. [13])

the “Physical” portion collects real-world data before sending it to be processed. In exchange, the “Virtual” part uses its embedded engineering models and AI to find information used in the “Physical.”

4 The Technologies for Applying DT

DT applications use a variety of data-related, high-devotion displaying, and model-based simulation advancements. Sensors, radio-frequency identification (RFID) tags, gauges, readers, scanners, cameras, and other data-related technologies are used to create data, which are the foundation of the DT. These gadgets generate massive amounts of unstructured, semi-structured, and structured data regularly. Because transmitting the relevant data to the DT in the cloud server is complex and expensive, edge computing preprocesses the data acquired. 5G technology is used to exclude the chance of data leaks and provide real-time data communication [44]. He et al. [28] explored how IoT and signal processing algorithms and approaches can be used in DTs to collect real-time data from many sources.

The adoption of high-fidelity modeling technologies necessitates the construction of DT models. Physical or semantic data models can be used to create DT models [44]. Semantic data models are educated using AI approaches using known data sources and yields, while actual models require an exhaustive comprehension of their actual characteristics and current connections. A multi-physics approach is required for the high-fidelity simulation of DTs [44]. Negri et al. [52] created simulation modules that mimic particular industrial equipment behavior. The primary simulation model used standard interfaces to connect with the modules and facilitated simulation throughout the production system's life cycle [54]. As a result, DT can be constructed using various modeling levels.

Simulation is an unavoidable feature of DTs when model-based simulation technologies are used. The DT simulation allows the virtual model to interact with the physical entity two-way in real-time. Schroeder et al. [66] recommended using Automation Markup Language to design attributes connected to the DT to determine the two-way interaction with the physical side. The model proved effective at sharing data among the DT's many systems [54]. Despite the gradual reception of DT in the assembling industry, the idea's contextualization in different areas, such as the construction sector, is as yet in its early stages [53]. As a result, significant efforts should be made to use DT in the construction sector to address the industry's complicated difficulties.

Most of the technology used in the industry could be affected by DT. For instance, as-built BIM for facilities' management [75], designed to offer information on the condition of buildings when they are commissioned, cannot offer an updated depiction of the building's present state, and DT can help with this situation. Several data-collecting technologies create information used in isolation for construction monitoring [54]. There are only a few circumstances in which more than one technology is used. The difficulty is maintaining a unified and integrated strategy in which numerous monitoring systems may feed data into a project data to serve numerous administrative activities. DT can propose a comprehensive and incorporated utilization of these advances to give a fruitful method of construction managing and controlling.

5 DT Implementations in the Construction Sector

As interest in DT grew, the construction sector began to follow suit in this area. While DT and BIM definitions may appear identical, construction experts have pointed out the differences between the two ideas. Although BIM and DT have certain similarities, according to Khajavi et al. [35], they differ in several aspects, including the objective, technology, end-users, and facility life stage. In the body of knowledge of construction, the applications of BIM have been thoroughly researched. The architects and engineers do not operate BIM with real-time data [35]. However, they use BIM to perform clash detections and material simulation during the project design phase and contractors to perform production controls, construction analysis, site management, and security management [76].

On the other hand, by analyzing real-time parameters, the DT monitors the physical asset and optimizes its operational efficiency [35]. For example, a building's DT can be utilized for operation and maintenance by allowing facility managers to undertake what-if analysis, improving energy efficiency and inhabitants' comfort [35]. The data gathered by a DT during the facility's operation and maintenance phase could be recorded in a database, and architects would use it on future designs [60].

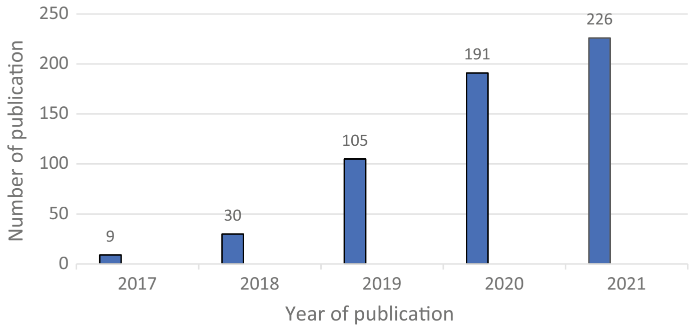

Fig. 3 Trend of DT publications in the construction sector

Most of the DT uses in construction are in the facility's operation and maintenance phase, whether the project is residential or industrial. The phrase "DT" is not explicitly addressed in most articles and is sometimes referred to as BIM or BIM-based facility management system (BIM-FM),existing literature on DT in construction is challenging to find [31].

However, from the notion began to shift from its contextualization stage to an initial stage in the construction business, there has been a constant rise of 191 papers in 2020 and 226 in 2021. Figure 3 shows that the increase of research papers focused on the DT within the construction field depends on research done through Google Scholar using keywords such as construction digital twin, digital twin and construction, and digital twin technologies within construction sector. Researchers have begun to look into the real-world uses of DTs in the construction sector. Some of the publications covered more than one step of the lifespan and were thus counted multiple times in each phase [54]. The majority of DT implementations in the construction sector were concentrated on a single life cycle phase. Investigators were preoccupied with the architectural and construction part of the project, but they overlooked the use of the DT concept throughout the demolition and recovery phase.

6 DT Application in the Life Cycle Phase of Construction Projects

The initiation, design, implementation, operation and maintenance, and demolition of construction projects are all parts of the life cycle. A holistic approach is required to manage the project lifespan from design to maintenance, operation to recycling, logistics to monitoring [21, 47, 58, 80]. Throughout the project lifespan, data are abundant. As a result, massive amounts of data gathered from design, production, procurement, resource management, logistics, utilities, and maintenance data sources have a ton of potential for further developing structure life cycle management operations as far as predictive and preventive information feed [34, 58]. With ongoing data use bringing about excellent, further developed precision, unsurprising cycles, superior execution, further developed information concentrated frameworks and services, and different advantages, extensive data might turn into the establishment of construction organizations' upper hand in expanding proficiency in design, production, operation, and maintenance [56, 69].

6.1 Design and Engineering Phase

The iterative optimization of the models shortens the whole design phase and eliminates the risk of extra costs during rework [41]. A construction project progresses through a series of stages [25]. Inception, brief, design, and engineering are all included in the design and engineering stage [20].

By permitting data to be added, changed, and checked against real-life scenarios, BIM models aid in the resolution of problems among various construction parties and decrease conflict among project stakeholders [62]. BIM use has seen significant advancement in terms of maturity in technology, process, and policy [72]. Hardin and McCool [27] stated that in addition to 3D models, BIM requires remarkable changes in project delivery and workflow operations. For DTs, BIM can allow visual, three-dimensional communication. The use of the sensors that monitor and collect data and BIM together creates an active model that can be used to implement DT in the construction industry [42]. The point at this issue supplies designers with helpful knowledge during the project's design. Designers can use DTs to get a complete digital footprint of a project and make informed judgments [74]. Data gathered with DT can be saved in a dataset and utilized by architects in ensuing ventures [60]. Collected data can aid in material and supplier selection, energy and supply chain management, and others. Furthermore, early design decisions regarding project feasibility, sustainability issues, and more topics could be informed using BIM and serve as guidelines for pre-construction [30].

Lin and Cheung [42] proposed advanced monitoring and control systems for underground garage environment management using BIM and Wireless Sensor Network (WSN) technologies. WSN has been used to monitor and record physical conditions, and they discovered that their suggested system was an effective system for environmental monitoring. Lu et al. [45–47] argued the use of semi-automatic geometric digital twinning depends on images and CAD drawings for existing buildings. Moreover, a case study on a portion of an office building has been conducted. They discovered that DT-conducted applications are a practical approach in the building's operations phase. It was also explored the gap between geometric digital twinning and existent structures. For the initial product development and study of multiple design ideas, the authors used high-resolution models. Using a DT help with digital fabrication planning has been discovered by the study as well.

6.2 Construction Phase

The construction phase, also known as the production phase, is where the finished product is created. The majority of studies using DT technology throughout the project's construction period has zeroed in on deciding the object's primary framework respectability. The notion of the DT is utilized to analyze the structural system integrity in historical masonry buildings [4]. The authors created a simulation model for a historic masonry building for DT applications. The study found that employing DT technology, structural behaviors at various stages of the building may be easily comprehended. In addition, the authors found that DT models, particularly in complicated portions of the masonry building, can be regularly updated utilizing the knowledge gained. At the point when forces are applied to the structure, the object's structural systems guarantee that the item does not fizzle [54]. For example, significant damage to the Milan Cathedral was reported throughout the last century, demanding significant restoration efforts [50].

Shen et al. [70] demonstrated a system integrating facility life cycle information via an agent-based web service. The goal of this approach was to use data collected throughout the project life cycle, from planning to design to construction, to help facility managers make better decisions. BIM and real-time asset tracking and real-time assessment monitoring technologies like wireless sensors and RFID were used to create the suggested information integration framework. It is worth noting that this integrated method has been successfully used in two industrial projects, however, the authors were unable to publish the results due to the nature of the industries.

6.3 Operation and Maintenance Phase

The project is typically out of the constructor's control during the operation and maintenance phases. As a result, managing and gaining access to the object's data become complicated. The virtual model could be a replica of the thing, but it has no connection to the actual project [3]. At this stage of the project, the project's users are concerned about its reliability and convenience. Several stakeholders are involved in the project, which prohibits data from being integrated between processes and stakeholders. DT can improve information flow between diverse stakeholders. DT is used in monitoring, logistics operations, facilities, and energy management during the project's operation and maintenance phase.

Lin et al. [43] developed a novel mobile-automated BIM-FM for usage by facility management technicians during the operation and maintenance phases. A commercial building project was used to test the mobile BIM-FM system. The results confirmed the system's performance, opening the door for facility management workers to be more efficient and more accessible data updates from facility management to the BIM environment. Peng et al. [57] investigated an airport terminal and demonstrated the value of combining data mining, data analysis, and BIM for building operation and maintenance. Using BIM and sensor data in facility operation and maintenance provides a massive amount of data that facility managers may examine. Facility managers are frequently confronted with increasingly non-intuitive datasets as well as error-prone human data entry, posing a variety of issues. The authors proposed a BIM-based data mining approach to evaluate the accumulated data, extract essential rules and patterns, and detect erroneous records to address this issue. The BIM database is initially connected to a data warehouse in this proposed approach. The database is then cleaned using three different data mining methods: cluster analysis to uncover associations of similarity among records, outlier identification to clean the database, and advanced pattern mining algorithm to find deeper logic links among records. Rather than going over an overwhelming number of individual entries, facility managers deal with a few high-quality data records. Chen et al. [18] proposed a framework for automating maintenance work orders to improve Facility Maintenance Management (FMM) and decision-making. The FMM framework was built by providing an IFC extension for maintenance tasks that linked data from BIM and Facility Management Systems (FMSs). When BIM and FMS data were combined, component errors were shown, and geometrical and semantic information about the dialed component could be derived from BIM models. A modified Dijkstra algorithm can be used to construct the maintenance work order schedule automatically. The algorithm considers four factors: the type of problem, the level of emergency, the distance between complements, and the location. The suggested framework's viability was tested in both indoor and outdoor 3D situations.

Kaewunruen and Lian [34] demonstrated the 6D BIM for managing the life cycle of a railway turnout system. The authors used Revit-2018 software to create a 3D model of the system and discovered that the 6D aims at carbon footprint throughout the whole project life. According to the findings, DTs can be used to visualize and prioritize maintenance alternatives. Antonino et al. [5] found that real-time and historical data on usage of a building are precious to building managers. They can improve building maintenance and services as well. The authors employed image recognition to monitor people's walks in an office building and provide real-time usage statistics. The authors discovered that real-time data on the flow of individuals traveling through a monitored location could be used to create smart contracts. On the other hand, the authors found no problems in integrating real-life data collected with image sensors to the BIM model.

Moreover, in various case studies, the authors did not test the suggested approach to improve their application in facilities management. By creating DTs for bulk silos, Greif et al. [22] looked into possibilities for construction site logistics. They created and deployed a decision-making system for silo replenishment and dispatch. The authors discovered that a successful decision assistance system requires a structural and visual display of insights. According to the study, silos can serve as both transport units and temporary storage facilities, allowing products to be transported to large urban areas for free.

6.4 Deconstruction and Recovery Phase

Researchers usually disregard the inactive phase when the facilities lose their functions [44]. In terms of using DT technology in the construction sector, the deconstruction and recovery phase, identical to the inactive phase, has also been overlooked. Knowledge of an object's behavior is generally lost during the deconstruction and recovery phase [54]. Grieves and Vickers [24] stated that as the things may share similar qualities, knowledge about the precursor of the next generation of the object might be utilized to tackle comparable issues that would arise. Liu et al. [44] stated that a low cost might be maintained in the virtual environment because the deconstruction and recovery phase provides information on the complete life cycle phases. Barazzetti et al. [9] described how to create detailed Historic Building Information Modeling (HBIM) utilizing augmented reality and virtual reality to increase user interest in cultural tourism. Integrating DT and HBIM procedures helps improve data management efficiency. The combination of DT and HBIM processes can also assist building managers in identifying potential dangers, technical solutions, and possible measures to take, as well as their actual implementation, in terms of asset conservation [33].

7 DT for Construction

By superimposing perceived DT skills and features from neighboring domains onto construction site multidimensional BIM usage, Boje et al. [13] emphasized the significant considerations related to deploying and using a DT during the construction stage.

Table 1 lists some recurring themes in the literature related to DT, which are divided into three categories using the Virtual–Data–Physical paradigm. Each subpart is regarded as a feature or "ability" of the DT that is thought necessary to facilitate various services. These competencies are applicable throughout the building life cycle, but the technologies and techniques employed at each stage vary.

DT is considered to contain all "valuable" information throughout the whole product life cycle in the manufacturing industry [15]. This valuable information holds for building and infrastructure life cycles as well, but on a much bigger scale and with essentially different dynamics, it affects how the built environment is designed and managed through the use of digital assets [46]. The construction DT's (CDT) capabilities are based on several processes and data layers aimed at facilitating smart construction services and applications [73]. These might benefit from DT integration on numerous levels, assuming that a solid framework is in place to accommodate the different heterogeneous systems and technologies encountered in research [63].

Current construction site detection efforts are restricted to routine laser scanning, manual management updates, and a variety of forms and papers human inputs. This hinders the ability of BIM and ultimate DT to accurately mimic and anticipate in

Table 1 Identified DT abilities and their roles within the virtual–data–physical paradigm (adapted from: Boje et al. [13])

Part	Ability	Description
The physical	Sense	The capacity to notice the actual world progressively through the utilization of sensors
	Monitor	The capacity to follow along, illuminate, and issue admonitions on significant actual adjustments
	Actuate	The capacity to change/initiate/deactivate actual parts dependent on virtual choices/boosts
The data	BIM	The capacity to incorporate and devour BIM explicit informational indexes in its different arrangements and norms
	IoT	The capacity to incorporate and share data imparted by the Internet of Things gadgets
	Data linking	The capacity to coordinate and share data by means of Semantic Web conventions
	Knowledge storing	The capacity to store realities about the framework, support rules, and reasoning abilities
The virtual	Simulate	The ability to apply engineering simulation models from various application domains
	Predict	The capacity to foresee the conduct of the actual dependent on advanced recreations and detecting
	Optimize	The capacity to apply streamlining strategies and suggest savvy distribution of assets progressively
	Agency	The capacity to designate AI specialists fits for overseeing (and inciting) the actual dependent on advanced data, following distinct practices, conventions, and targets

terms of multidimensional modeling, as the information is out of date and out of sync with the physical twin [61].

The researched 4D BIM use cases demonstrated the emergence of trends and technology for capturing site data and automating BIM during construction. These technologies use a variety of site scanning procedures and reflect them in BIM [26, 37]. Several research projects have previously referred to the issue of interpreting the massive volume of data transferring through a building site to its digital model and the difficulties of fitting and retaining construction site sensors [1]. As a result, problems persist in verifying data (completeness and accuracy), appropriately interpreting it (using semantics), and processing it in a way that allows for real-time responses [13]. Automated site monitoring approaches would initially help site logistics [26] and safety [79].

Furthermore, visualization is crucial in the construction industry, as it is at the heart of intercommunication and decision-making. The utterance "drowning in data" [71] may be crossed with proven methods of visualization of data for managing projects by using actual, real-time feeds from multiple sources if holistic and enhanced real-time site surveillance is provided.

The dynamics of a construction site revolve around properly organizing work, keeping expenses within budget, and judiciously employing resources. Suppose that a more integrated complicated structure, the DT should dynamically update schedule and cost information in response to rapidly changing site operations, activate the appropriate estimating algorithms, and notify management by delivering timely warnings on interruptions and their likely causes [13].

Construction sites have long been seen as one of the most hazardous places to work. Various studies and professionals understand the benefits of adopting 4D modeling and believe that it has a built-in benefit for improving health and safety. However, given the way data are collected in the field, the process of applying safety management through systematic and relevant procedures with definite indicators is still absent. The existence of workers on-site, their numbers, and positions should be recorded by construction DTs. It could even catch potential anomalous behaviors like immotility, falls, or also monitor their exhaustion and attentiveness during dangerous activities [77], in addition to monitoring compliance with safety requirements.

Building practitioners are typically hesitant to adopt such innovations despite the added value since they cannot rely on the completion or validity of BIM data all through construction. The related personal endeavor required to achieve suchlike BIM utilization is a significant obstacle that automated detection can overcome. As a result, Boje et al. [13] deemed sensing along with semantic enrichment of BIM models as a foundation for n-dimensional clash detection simulations. Therefore, the DT would demonstrate the current situation and allow construction teams to execute alternative planning simulations, such as tasks, logistics operations, or equipment allocation plans.

Moreover, construction productivity is hampered by a lack of integration between on-site and off-site operations and supply-chain actors. While micromanagement may improve on-site daily operation, these tasks are also considered to be carried out if there are prerequisite tasks (including material/equipment delivery from off-site production systems) related to the entire supply chain. Lean construction approaches, such as the Last Planner System [8], typically rely on forms, data collecting from all parties, and planning ahead of time. On all levels, however, there is still a lack of practical information integration. Semantic DT applications promise the capacity to interconnect diverse datasets as well as connect various planning systems [36]. In such negotiation-intensive management approaches, AI may also provide value to human agents by counseling experts on optimal duration, sequencing, and other factors. Construction processes and related off-site and on-site resources should be modeled, tracked, and optimized using the Semantic DT [36].

As-planned BIMs can change drastically during the structure stage; for instance, determining equipment for a specific manufacturer might change during purchase orders, diminishing expenses, or guaranteeing that equipment is accessible inside the project's timetable. Project supplier information, products, and order modifications can be linked over the web to assist in lessening the impact of such disruptions on production [13]. Additionally, transmitting a broad context of essential suppliers and items for use during future maintenance and prospective upgrades would improve the transition from handover to the operation of the supplied facility. As evidenced by the literature, web-based IoT integration is in demand across the board in the urban environment. As a result, the shift from construction to operation must consider the needs of the larger urban environment [2].

8 Value and Benefits

Boje et al. [13] suggested a development paradigm of the CDT. Other industry perspectives have been considered [14], laying out a five-step approach for developing a DT during the construction stage. However, due to the absence of application and research at specific degrees of complication, there is still a problem on understanding of the prospective technologies for higher levels. They believed that CDT implementation efforts should be gradual but constant throughout the life cycle of a building, considering supply chain integration and the complication of technologies used. Virtual models and sensing might eventually mix to establish a well-formed web platform. Adoption of traditional tools and formats is dependent on the application domains and current models, but it would be a crucial step toward interoperability and further life cycle phases. Implementing advanced types of AI is the last step that is predicted to happen after enough training and verification of AI behavior have been completed, this marks the transition of some tasks from human expert control and guidance to limited DT agency [13].

When examining the importance of a construction company's value chain management, the gains of implementing a CDT must be thoroughly evaluated for each type of project (basis of scope, customer needs, procurement methods, etc.). In comparison, increasing its earnings and adding value to its clients also reduce its costs of implementation [13]. While BIM is a part of the initial procurement and demolition phases, CDT's focus should be on building the "Physical Twin" during pre-construction and construction phases [48]. While BIM procedures and models can enhance cooperation with the application of uniform standards and size, the BIM paradigm for IoT and dynamic site data is restricted. A CDT presupposes cohesive, synchronicity-enhanced integration of models, sensors, and services. The implicit advantage would be gained in enhanced constructional services, which would enable the building processes to better assigning resources for activities that are completed better using robots, drones, and sensors and for those requiring human resources [13].

The value of DTs is quantified in the extra benefit to society they provide by supporting lower carbon emission and clean energy objectives [49]. The ability to adapt to the various systems that dwelling around the man-made environment is now a research challenge. Many intelligent building management systems, which must better adapt and react to inhabitant requirements while also optimizing resource consumption, are limited by the dynamics of human interaction with constructed assets [55]. Applying this to the construction site, a CDT should access all of the project's data, understand the overall context, and provide relevant insights [39]. In addition, the use of the CDT, which varies according to the applications' domain over the life cycle [65], should be possible for users of different social and educational backgrounds.

9 Conclusion and Limitations

Interoperability, inefficient integration, inadequate information management, operational issues, a lack of data in facility management, and hurdles to knowledge usage and management all afflict the deployment of DTs throughout the life cycle of a building project. This chapter provides an overview of the implementation of the DT in construction projects through their life cycle. The framework's examination revealed that while the construction industry has made tremendous progress by moving beyond the digital model, the implementation of DT is still not fully realized in the industry. However, it may be stated that the study focus is currently shifting to DT. Since the inception of BIM, the construction industry has made tremendous progress, gaining enough awareness and momentum to permit a change from a static, closed information environment to a dynamic, web-based one that embraces IoT connectivity, and a higher degree of AI application. Increased automation and cohesion of information would help provide better construction services.

The impact of DTs on the construction sector has been demonstrated in this review through the many life cycle phases of the object. DTs offer the possibility of proactively addressing problems before they arise. The use of DTs during the design and engineering stages can aid in determining elements and information that should be acquired or wiped out during the object's redesign and re-engineering. Further studies will necessitate in-depth investigation into the use of DTs during the design and engineering phases of a construction project. In the construction phase, the job of the DT is to minimize construction costs efficiently and effectively while also improving quality, which is something that the old method cannot deliver. The structural system completeness of the entity during the implementation phase has been the topic of some extant literature. More research into stakeholder management, quality management, cost management, and value management is required during the project's building phase. In the long term, the building project stakeholders will benefit from DT's application to an intelligent project life cycle management by innovative and lean building processes. Furthermore, the chapter specifies the number of DT capabilities or characteristics that allow for real-time, web-based, intelligent CDTs.

This study has some limitations despite its contributions. Only the databases Scopus, Web of Science, and ScienceDirect have been used for organizing the research. Despite the rigorous selection of relevant publications, it can be possible that not all keywords were captured in the literature search. Subjective judgments may have influenced the selection of relevant articles and the identification of applications in the various life cycle phases during the literature study. The abovementioned limitations provide fertile ground for future study and should be addressed when evaluating the research findings. This study suggests using a wider range of datasets and conducting more comprehensive literature research.

Future studies should analyze the construction industry's readiness to integrate digital twins into its operations completely. This will increase practitioners' grasp of the idea of digital twin. Additionally, future studies should look at the crucial success factors and challenges to effective digital twin adoption in the construction sector. This will increase the urge to use digital twin to solve the construction sector's difficulties. Furthermore, this study investigated the use of digital twins in the various life cycle phases of a construction project. This can help practitioners grasp and accept the notion of digital twins. However, further study is required to investigate the potential uses of digital twins.

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An Interactive Digital Twin Platform for Offshore Wind Farms' Development

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1 Introduction

During the last two decades, modern power systems are rapidly decarbonizing toward higher market shares of renewables by using wind and solar energy. Especially, wind farms are attractive solutions to handle energy crisis and to reduce greenhouse gas emissions, whereby offshore wind farms are particularly appealing due to their minimum environmental effects and the abundance of wind. According to the GE Renewable Energy Report [1], it is expected that the offshore wind industry will grow from 17 to 90 GW in the next decade and that offshore wind power will account for 15% of the global wind industry going forward. Such an expectation seems not exaggerated, noting that the Global Wind Report concludes that 2020 was a record year for the global wind power industry despite the impacts of COVID-19 with 93 GW of new capacity installed—a 53% year-on-year increase [2]. In addition to the decarbonization aspects, power systems, including the offshore wind industry, are using the advantage of digitalization technologies to increase efficiency, to provide safer solutions, and to reduce the cost of existing conventions. The offshore wind sector accommodates a very fruitful playground for the joint use of decarbonization and digitalization practices. In other terms, offshore wind applications can be considered as one of the most important drivers toward the Digital Green Transition of the entire energy sector.

Offshore wind farms are usually located hundreds of kilometers from their control centers. To operate the wind farms, sophisticated Supervisory Control and Data

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_13

Acquisition (SCADA) systems are used to give operators complete control and to collect and analyze data. For several years, SCADA systems have been successfully implemented in the wind farm industry, providing valuable information about the present status of individual wind turbines. In the era of Industry 4.0, where data from physical assets like wind turbines can be accessed via the internet, disruptive technologies such as digital twins can potentially be used to support or replace the SCADA system. A digital twin offers a much more advanced level of information and perspective since it can provide not only the present status but can also depict the past and the future. According to Subhankar [3], the digital twin concept has started to revolutionize wind operations.

A wind farm can be considered as a cyber-physical system, in the sense that the system can be controlled or monitored by computer-based algorithms. Digital twins can be used not only for monitoring the conditions of offshore wind farms, but also to simulate different scenarios for operational purposes. A digital twin can be defined as "a virtual representation of a physical asset enabled through data and simulators for real-time prediction, optimization, monitoring, controlling, and improved decision making" (Rasheed et al. [4], p. 21980) or simply as the current digital representation of a product or a system that mimics a company's machines, controls, workflows, and systems [5]. Pal [3] emphasizes an important benefit of a digital twin when he defines it as a digital "mirror" of a physical asset allowing users to see what's going on "under the hood" without the need for being physically present. The latter is enabled by placing sensors that can collect real-time data and operational status on the physical asset, for example, a turbine, that can then be sent to a computer program for interpretation in the form of raw data or a three-dimensional (3D) representation [6]. Figure 1 illustrates such a setup.

Besides augmented reality frameworks, digitalization and digital twining of wind farms and associated energy systems consist of various building blocks such as communication technology, blockchain technology, data analytics, and visualization methodologies. There are several types of digital twins that exist in literature, such as digital twin prototype, digital twin instance, and digital twin aggregate [7]. Each of these digital twin types serves different purposes. In this chapter, we introduce the concept of an interactive digital twin. *We define an interactive digital twin as a digital twin that can be used to assist asset development and optimization through interactive simulation based on augmented reality.* The importance of the interactive simulation is emphasized in the review of digital twin solutions [8], especially by applying VR, AR, and MR technology in heavy industries [9]. The Unity3D platform is evaluated to provide good performance to visualize the interactive simulation [10].

In what follows, the potential use and need of digital twins in the field of wind power will be discussed. In addition, we present insight to the development of an interactive digital twin platform for offshore wind farms and its associated electromechanical components. The digital twin platform is combined with augmented reality to enhance user experience. The interactive digital twin platform is based on the OPC UA (Unified Architecture) for communication, Unity3D for simulation and visualization, and Vuforia for augmented reality. We use the Hywind Tampen wind farm as a use case. The digital twin enables users to simulate different wind

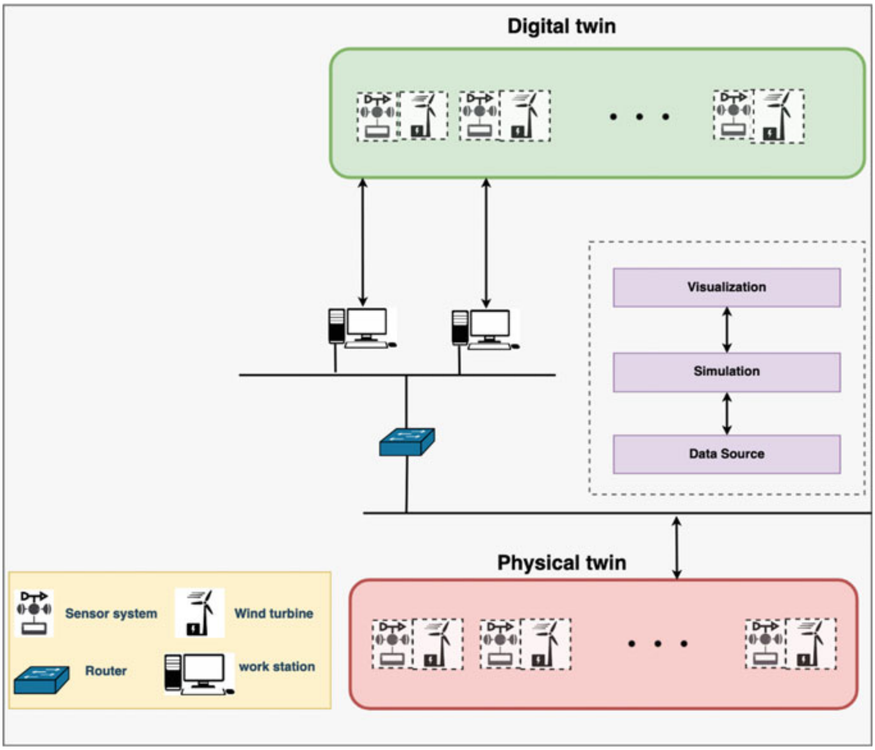

Fig. 1 Typical digital twin setup

speeds and wind directions, as well as the associated geometry and capacity of each wind turbine. These features additionally enable users to simulate different scenarios related to further development and optimization of the wind farm.

2 Digital Twins of Offshore Wind Farms

Digitalization has been on the agenda of the offshore wind industry in the past fifteen years. Digital twin technology is expected to lower the Levelized Cost of Energy (LCoE) for offshore wind farms so that they can compete with fossil-based energy resources. In the offshore wind industry, digital twins can be used to reduce design, construction, and operational costs. In the design phase, digital twin powered by high-performance computing shorten analysis time. Furthermore, digital twins also enable automated and interoperable design workflows. Within the construction phase, if we introduce 4D construction simulation on the physical assets, then we can achieve improved sequence planning and scheduling of the project. As regards operational and maintenance phase, we can improve risk management by using digital twins from

Fig. 2 Wind farm (left) and its digital twin (right)

the design to operation stages. Moreover, we can also leverage augmented reality models for digital retrofit and maintenance. Figure 2 shows an illustration of a digital twin for an offshore wind farm. By having a digital representation of the physical wind farms, the operator can simulate different scenarios and predict component failure that may occur in the future.

To demonstrate the value of interactive digital twins for the wind industry, in the next sections, we design an interactive digital twin for the Hywind Tampen floating wind farm. The wind farm, upon its completion, will be the largest floating wind farm in the world and consists of 11 wind turbines with a combined capacity of 94.6 MW (8.6 MW each). The wind farm is intended to provide electricity for the Gullfaks and the Snorre oil field and is estimated to meet about one-third of the annual electricity power demand. Furthermore, it is expected to reduce 200,000 tons of carbon emission per year.

3 Development of an Interactive Digital Twin Platform

In this section, we describe the structure of our proposed interactive digital twin platform. The platform was developed at the Department of ICT and Natural Sciences, Norwegian University of Science and Technology (NTNU). It has been used for teaching and research purposes. The platform is continuously improved by students and researchers. The functions marked in gray color in Fig. 3 are customized options, while the remaining functions are classified as standard functions provided by the interactive digital twin platform. Figure 3 also shows the schematic diagram of the platform, which consists of three component layers: the data source layer, the simulation layer, and the visualization layer. These three layers are all connected by a communication protocol based on OPC UA.

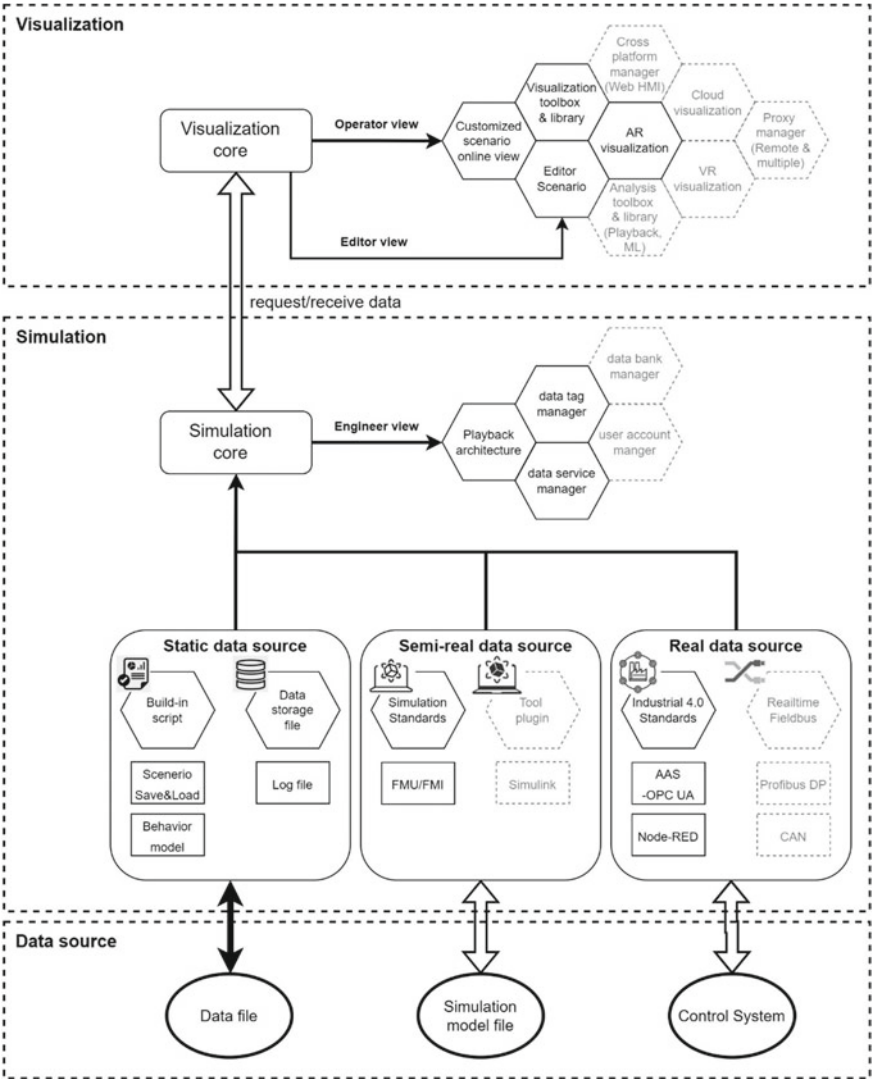

Fig. 3 Schematic diagram of the interactive digital twin platform

3.1 The Data Source Layer

Digital twins require data from various sources with different data types to facilitate the creation of a virtual model that can represent the behavior of real physical assets and their operation. Once we have a digital twin in place, it can be used to create simulations and to predict and analyze how the physical twin will perform. Data sources to be used in a digital twin can be of many types, such as visual data, measurement data, and historical data. In the interactive digital twin platform that we have developed, data sources are classified into three main types: static data source, semi-real data source, and real data source.

- The static data source includes data files which are normally created automatically when we set up a simulation scenario. It can be configuration files for parameters and scenarios or just logs data for sample scenarios.
- The semi-real data source is the simulation model file, which involves the model equations or constrains to create the simulated data.
- The real data source is normally provided by the control system. This includes the output of the sensor systems at run time to control the behavior of the physical assets.

3.2 The Simulation Layer

Model-based simulation can be used in the engineering design and optimization phase. Simulation is usually performed to do "what if" scenarios based on dynamic models of the system. In practice, complex systems such as wind farms can be simulated at their component level by using different software. To capture the dynamic behavior of the overall system, each simulated component needs to be simulated at the same time. This process is called co-simulation. Using a Functional Mock-Up Interface (FMI) is one way to exchange data between dynamic models. It is an independent standard, which includes Model Exchange (ME) and co-simulation (CS). It defines a container and a combination of XML files, model files, etc., into a single file. The model file is called Functional Mock-Up Unit (FMU). The difference between an FMU-ME and an FMU-CS is whether the simulation tool includes solver (FMU-CS) or not (FMU-ME). FMI Version 1.0 was released in 2010. It consists of all the basic FMU concepts such as ME and CS. In 2014, FMI Version 2.0 was published. It adds some functionality compared to the previous version, such as support for directional derivatives, and clarifies ambiguities in the 1.0 standard. On February 19, 2022, the FMI Version 3.0 Beta.4 was pre-released, supporting two kinds of clock-based simulations: Synchronous Clocked Simulation and Scheduled Execution. This version is designed for real-time co-simulation. In our development, we used FMU 2.0 CS since the original model file for wind turbine is in MATLAB and since it only supported FMU-CS. The simulation layer has one core mission into controlling functions as playback, manage data service and data tags in the engineering mode, as well as, among others, management of data bank and user accounts. It also includes connections to static, semi-real, and real data sources.

3.3 The Visualization Layer

The visualization layer has one primary objective in supporting the operator mode and the editor mode with the user role. The editor can freely configure different scenarios with inventory (wind turbine, oil rig, etc.) and dashboard widgets (slider, button, input fields, charts, gauges, etc.), while the operator can access them during daily operation, labeled as "Customized scenario online view" in Fig. 3. The functions "Visualization toolbox and library" and "AR visualization" are essential for the interactive digital twin, while the others are optional. For example, machine learning (ML) in the analysis toolbox can be added for data prediction.

3.4 The Communication Protocol

There are several communication protocols that can be used as our solution. To simplify the development and easier deployment of clients, we choose to use Node-RED to act as a bridge, as shown in Fig. 4, to synchronize serial port data to OPC UA server namespace. Node-RED is a flow-based programming tool, originally developed by IBM's Emerging Technology Services team, now being part of the OpenJS Foundation. Node-RED has leveraged a robust API platform that provides a wide variety of online services for securing and programming hardware devices to connect physical assets to digital assets. It is perceived highly efficient and easy to understand for rapid prototyping, especially if the number of variables is less than 100. OPC UA and serial communication blocks from Node-RED are deployed to connect sensor data into the digital platform.

4 Experimental Case Study

The experimental setup consists of physical asset and its digital twin. The physical asset includes wind turbines, a fan to generate the wind, and sensor systems to measure temperature, wind speed, and wind direction. The schematic diagram for the experiment is provided in Fig. 5. The commissioning site consists of physical assets. Data from the sensor systems will be transmitted into the server.

The experimental setup is based on our proposed solution. It has been implemented in Unity3D providing a customized interactive 3D visualization platform, MATLAB Simulink and Simscape as model simulator, FMU/FMI for co-simulation, OPC UA as communication protocol, and using the Node-RED tool offering APIs and online services, all providing standardization of interfaces and data format. The following subsections describe steps in the experiment.

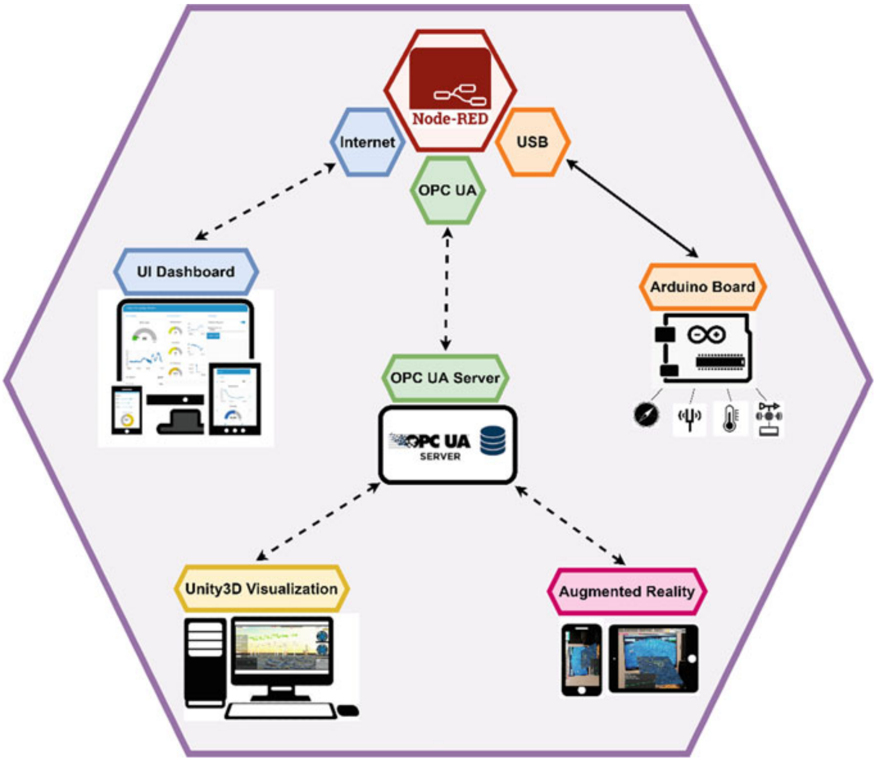

Fig. 4 Overview of the Node-RED logic with drag and drop, simple scripts

4.1 Data Source

In this experiment, the data files are the project data format defined to save the log data, scenario configuration, and parameters for the behavior model. It connects the built-in script in the Unity3D platform pertaining to the simulation layer. The simulation model file in MATLAB works as the data simulator to export the simulated data from more complex physical models to the simulation layer by FMU/FMI (Sect. 3.3). The control system is the core of the physical twin, which is implemented by the use of Arduino UNO and a group of sensors and motors. It is connected to OPC UA protocol by the use of typical industrial serial port.

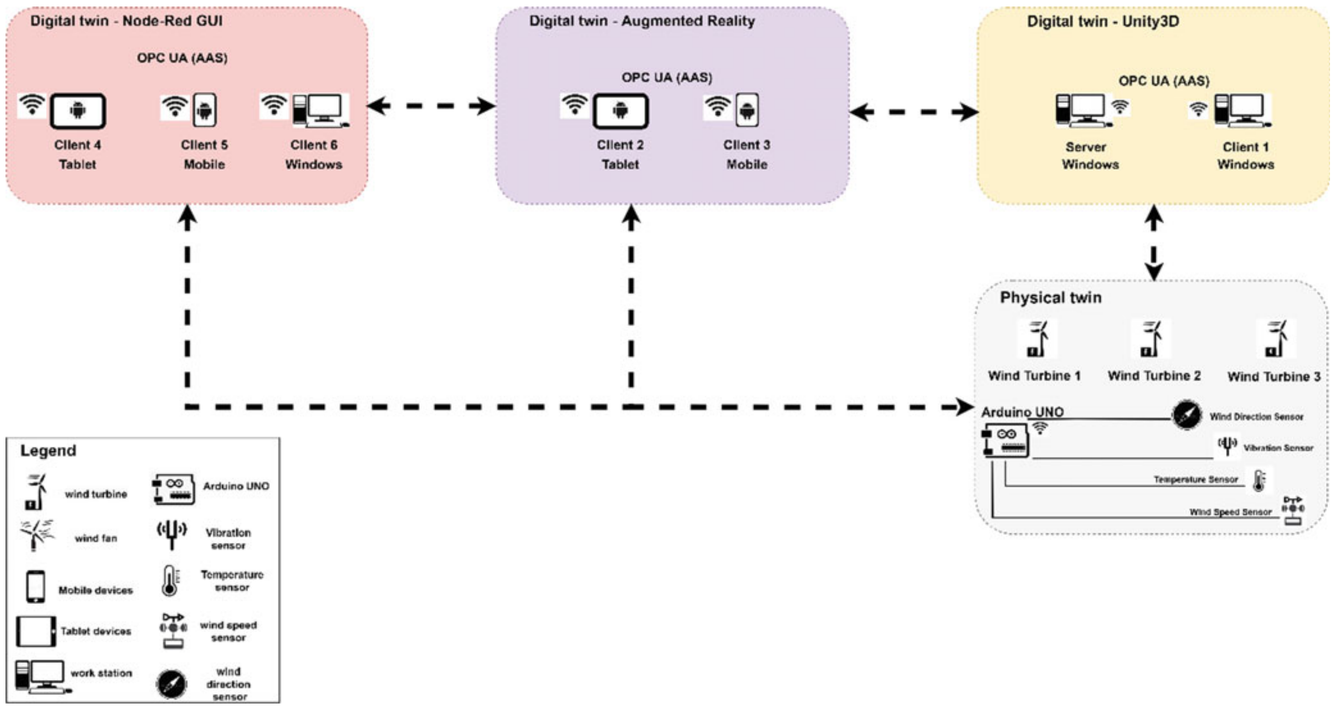

Fig. 5 Experimental setup of an interactive digital twin for the Hywind Tampen wind farm

4.2 Simulation

The Unity script includes a simplified wind turbine power calculation model, while the simulation layer supports the critical FMU/FMI support. The package Unity-FMI-Addon is imported to auto compile the corresponding .dll file and function definition codes. Afterward, all port variables could be read and write during the simulation process, while the .dll file has been converted as a Unity asset file (.asset). The execution of the simulation is strictly controlled by the time step function with the given time value and input variable values. The output variables marked as data tags are parts of the data sources of the visualization layer, such as output power, power coefficients, wake loss.

4.3 Visualization

The visualization layer reflects the reality using the visualization toolbox and libraries. In our solution, Unity3D is chosen as the development tool due to its powerful technologies for efficient and high-quality visual effects and AR support (Sect. 5). The Universal Render Pipeline is used for wave and wind simulation. The visualization layer includes parameters and configuration of visual effects for different users. To get a good balance between quality and render speed, design engineers normally conduct experiments by using different parameters. For example, wind effects could be implemented by the use of a particle system, Unity3D, or other third-party packages.

Finally, in an operator mode, the wind farm and wind condition can be controlled and set by parameters through sliders, input fields, and buttons. Output results are displayed both on gauges and line charts on the user interface and on 3D bar graphs on the top of each wind turbine. The editor mode gives the user access to more detailed data and configuration options based on requirements and applications.

5 Interactive Digital Twin Based on Augmented Reality (AR)

Augmented Reality (AR) provides an easy and more understandable visual representation of digital assets for users to interact. The AR technology is supported by a growing trend of mobile application developments. The option allows users to immediately access the digital assets from common gadget such as tablets and smartphones to obtain data and to adjust physical assets via technologies like Internet of Things (IoT), without requiring special tools or hardware or making use of a specific software. There are several solutions that can be used to implement this technology in the industry. In this chapter, we address AR solutions based on Unity3D and Vuforia.

Unity3D provides its own AR toolkit for which most digital platform-related solutions can be easily integrated. Unity's AR toolkit is a framework that enables developers to create an application and then deploy it to different mobile and wearable AR devices. Another alternative solution for AR is PTC Vuforia which is a powerful AR platform commonly used in industry. It offers different SDKs to build applications through Android, iOS, Windows platforms, and Unity3D equipped with a variety of features and trackable targets such as images, objects, and environments.

The Vuforia engine Unity3D SDK is the solution that we choose for applying and experiencing with the AR landscape on the experimentally implemented Unity3D wind farm platform. The AR scene in Unity3D implemented in the Vuforia plugin can be exported into different platforms such as Android, iOS, Windows, and macOS. Since it is easy to export and install, the Android system was considered as chosen as the preferred option for this experiment. Regarding the implementations, the .apk application can be created and exported by Unity3D and installed easily on mobile devices. After opening the application, the phone camera needs to be projected into a recognizable image considered as the target in Unity3D. The result is a unique intuitive landscape to be used to connect and interact with the created Unity3D visualization platform. It is easy to use and accessible from anywhere without requiring specific devices and tools.

Per se, the platform provides real-time data exchange and a bidirectional communication flow that gives the users the capability of processing wind farm data from the physical assets, as well as giving commands and getting feedback from both sides. All features available in the Unity3D platform are accessible in the AR scene, such as interacting with the wind farm by adding and removing objects, adjusting all settings, connecting to real-time data through the OPC UA. Any modifications by the user result in changes in the Unity3D and physical platform and vice versa. Figure 6 shows our interactive digital twin platform installed in Android, enabling users to simulate different scenarios and to predict energy output in the future.

Fig. 6 Interactive digital twin platform based on augmented reality

6 Conclusions and Future Works

Wind power have proved its maturity as an industrial segment and has become one of the most popular energy resources. Recent digitalization advancements such as digital twins are gaining momentum in the wind energy industry. This chapter has provided insight into some of the potential of digital twin development of wind farms by looking into the nuts and bolts of an interactive digital twin platform we developed by the use of Industry 4.0 standards combined with augmented reality to enhance user experiences. To increase the readers' understanding, a schematic diagram of the platform was provided, followed by descriptions of the data source layer, the simulation layer, and the visualization layer.

As regards the status of the platform, future work aims to improving the accuracy of the dynamic models of the individual wind turbines. It is expected that more advanced and diversified applications of digital twin will be observed in the future. Correspondingly, various other use cases and features are expected to be tested, whereby data management, data protection, and cybersecurity concerns will be covered accordingly.

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Digital Twin Applications in Spacecraft Protection

Hande Yavuz and Enis Konacaklı

1 Introduction

Spacecrafts are the most valuable assets for the space operations. They are the core technology which carries the dreams of humanity over the new horizons. Despite the importance and astronomical costs of the spacecraft operations, they face various challenges during their missions. A tiny error may trigger a chain of events that may cause the total failure of whole spacecraft operation.

Digital twin is the artificially designed digital copy of a physical being, in response to data gathered from this real object. Not only various decision-making and simulation technologies but also space technologies are benefiting from digital twins for enhancing its capabilities for the recent years.

These applications basically aim to improve structural design and analysis of spacecrafts. They also bring better quality both in manufacturing of components and in assembly process and secure the space travel as well as reduce the cost of those issues. While dealing with the complexity associated with the spacecraft function through the available heuristic methods and intelligent tools, data acquisition, data processing, and data analysis would provide feasible solutions using numerous features of the digital twin concept. In line with the scenarios and simulations prepared with the data got using *the digital twin technology*, the spacecrafts can successfully complete their missions.

In this chapter, technological development of spacecrafts is explained. The segmentation of spacecrafts is detailed into structural aspects, impact dynamics.

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_14

Spacecraft protection against traceable and nontraceable objects like space debris and micrometeoroids in different orbits is examined under the main contributions of digital twin technology in space operations.

2 Spacecraft Structure and Impact Dynamics

The scale savings, costs, investments, manufacturing and intellectual property rights, government regulations, consumer preferences, and distribution channels could realize the evaluation of spacecraft technology. The product types, applications, and their end industries have a driving force on the development of spacecraft technology. Noteworthy, risks and obstacles, solutions, and key products, revenue history, and prediction size of the spacecraft market maintain the spacecraft ecosystem.

Not only material technologies, engineering, and design but also structural aspects and impact dynamics strengthen the resilience of the spacecraft. The enhancements at these techniques built up the future of the spacecraft ecosystem. Thus, the spacecraft impact dynamics should have been understood to evaluate the use of digital twin technology for spacecraft protection.

2.1 Structural Aspects of Spacecrafts

Spacecrafts are in general composed of primary, secondary, and tertiary structures. Among those structures, stiffened shell semi-monocoque structural configuration is used in primary structures of spacecrafts such as in the body structure and launch vehicle adapter [35]. Primary structures provide the major load path between spacecraft's components and launch vehicle. They are usually designed for stiffness or natural frequency as well as they readily withstand loading due to the steady-state accelerations and transient loading during launch [19]. Especially, launch vehicle is vulnerable to severe aerodynamic loading besides launch loads. There are numerous secondary structures such as flexible appendages and solar panels, which may be adversely affected due to elastic vibrations, further considered as a primary cause for the instability, especially in the absence of active vibration suppression controller to the overall control algorithm [33, 40]. Most severe loading on tertiary structures such as on control boxes is caused by high-frequency vibration [35].

Structures of spacecrafts are not only designed to survive on Earth, during launch, and in space, but also preserve the function of non-structural components before and during the mission. Spacecraft structural design is mostly concerned with the space environment that varies in terms of thermal radiation, charged particle radiation, solar radiation pressure, neutral atomic and molecular particles, gravity gradient torque, aerodynamic torque, vacuum environment as well as impact of micrometeoroids and space debris [1, 8, 27]. Materials to be used to construct spacecrafts must also survive against time-varying forces, high internal pressure, radiation, thermal loading, and

Table 1 Sources of structural loading

Static external	Weight of components with regard to gravity and steady acceleration
Static self-contained	Pressure of mechanical preloads due to mechanical joints
Dynamic external	Load caused by repositioning of space vehicle and engine thrust
Dynamic self-contained	Mass loading of a vibrating craft, after the force that caused the excitation is removed

humidity as well. Moreover, the positional instability which usually arises due to plastic deformation, thermoelastic distortions as well as mechanical joint mispositions has to be considered in the frame of typical structural design. Cost-effective design solutions are indispensable since the growing interest not only focuses on crashworthiness issues but also on reusable parts [6]. Those are all in relation with the proper definition of the requirements, identification of options, performing structural and functional analyses together with trade-off studies in order to deliver a system suitable for launch and mission.

Structural design of spacecrafts requires clear identification of the sources of structural loading. Those are at first classified into four parts: static external, static self-contained, dynamic external, and dynamic self-contained [35]. Sources of structural loadings are summarized in Table 1.

Static external loads basically include the weight of components with regard to gravity and steady acceleration. Static self-contained loads come onto stage with the pressure of stored propellant, mechanical preloads due to mechanical joints such as bolts and springs. Dynamic external loads are caused by acoustic pressure, gust loading during launch, pulsed thrust because of repositioning of space vehicle, and engine thrust [12]. Dynamic self-contained loads can be referred to as vibrating spacecraft mass loads during environmental testing or in space after the force caused by the excitation has been removed. Among those structural loadings, launch generates the highest and most severe loading for most spacecrafts. Since spacecrafts have their specific launch stages, axial acceleration profiles may vary in different launch vehicles until payload separation. Those are designed in consideration with their mission profiles in terms of planetary, extra planetary, interplanetary, or lunar missions as well as their use and type could be referred to as unmanned and manned spacecrafts.

2.2 *Impact Dynamics and Spacecraft Protection*

Historical background of impact dynamics goes back to Galileo Galilei regarding his observations on lunar craters in the seventeenth century. Heretofore, there have been enormous contributions realized by many researchers which bring the impact dynamics phenomena to its current state of knowledge. Stress wave propagation beyond steady-state conditions, the inertia effects based on fundamental conservation of mechanics and physics as well as the material behavior under high strain rate of loading are included in the features of impact dynamics [36]. Conservation laws in terms of mass, momentum, and energy apply here accordingly [24].

To solve impact problems, using purely empirical approach requires large amount experimentation, data withdrawal, and processing using correlational methods. Quantitative and qualitative assessments are likely to be performed by using different methods in order to comprehensively characterize high-speed phenomena. Laser Doppler velocimetry for the research in solid-state shock wave physics and terminal ballistics as well as SIM-X UHS for study of the hypervelocity impact on lunar materials are some of the tools to be used together with those assessments [25]. Numerical approaches are frequently concerned within the computation of complex impact phenomenon supported by experimentation. General modes of failure are gathered upon experiments where stress fields are analyzed through numerical modeling. Apparently, those are used to verify engineering models in order to provide reliable results to investigate various impact cases. However, gathering the experimental data in the dynamic-low region by using high-velocity hydraulic/pneumatic machines or cam plastometer is performed with caution due to mechanical resonance. Moreover, at high strain rate testing, the effect of wave propagations as well as the inertial forces will increase with strain rate accordingly.

The classification of impact events roughly provides the velocity range of impact event. Hypervelocity impact events are referred as to micrometeoroid and orbital debris (MMOD) impact that are higher than 1500 km/h. Spacecrafts are vulnerable to MMOD impact during operation in Earth orbit if basically unshielded. Upon collision avoidance maneuvering, spacecrafts may prevent severe damages where the objects are as large 10 cm in diameter. However, microscopic objects may pose severe damages due to their large number of existences in Earth orbit [26]. Hence, effective prevention of spacecraft damaging as well as human protection for manned spacecrafts is the main concerns in spacecraft design to safely complete operation [19].

Spacecrafts, rocket bodies, fragmentation debris as well as mission-related debris are considered in Earth orbit. Those fragments may either be generated by collisions or explosions of satellites. Currently, number of those objects have been increased and reached roughly more than hundred thousand level [13]. Once the number of objects in Earth orbit was considered according to the available statistical data, fragmentation debris was found to be the largest companion in the total objects in Earth orbit compared to mission-related debris, rocket bodies, and spacecrafts. Among those objects, MMOD may cause damage and further lead to failure of components/parts when a spacecraft encounters such an impact. Hence, impact sensitivity assessment has been carried out by numerous researchers using various simulation software that run on different methodologies including theoretical assumptions. The orbital parameters of spacecraft such as orbital altitude, orbit inclination angle, eccentricity as well as launch year and time range play important role in the spacecraft protection. Space debris flux, environmental engineering model of space debris, and sensitivity analysis are provided in the survivability analysis of spacecraft components. In this regard, impact sensitivity analysis has been performed using NASA BUMPER, ESABASE2/DEBRIS, QinetiQ Shield, EMI PIRAT. Besides, the promising methods proposed by Trisoloni and Di-Qi Hu are also available in literature [13]. Concurrently, there are commercial firms which may help to reduce the amount of space junk by developing specific collectors as well.

Damage prevention of spacecrafts due to hypervelocity impact of MMOD threats could be realized by using various shielding structures. Conventional protection of spacecrafts, especially operating in the near-earth space environment, has been realized using bumper wall mounted basically on outer wall of a spacecraft called Whipple Shield [22]. Whipple Shield and their derivatives such as dual-wall Whipple Shield are developed to reduce perforation because of small and extremely high-speed projectile impact. MMOD impact at hypervelocity regime may cause the protective wall and further debris even to liquefy and vaporize. Dynamic tensile fracture strength of the inner structures of spacecraft could be exceeded due to possible rarefaction stresses created by the debris impact as well. Internal components such as electronic boxes, radiator linings, and cables may receive damage upon ejection of spall fragments. Except Whipple shield and its dual-wall derivative, multi-wall systems including intermediate blankets are developed. Those systems may include composite materials rather than aluminum sheets for the structural protection purposes.

Structures designed and built of metallic materials are well understood by means of three-dimensional solid finite element analysis and novel reduction methods to three-dimensional beam element and three-dimensional shell elements developed [18, 37, 38]. These can be easily understood as the materials are normally homogeneous and isotropic in nature. However, the composite materials that are used to construct spacecraft sections such as liquefied gas vessels are far from being homogeneous and isotropic and are essentially an assembly of fibers and the matrix in different orientations to balance the loads imposed on them. To date, most design approaches for composites are based upon layers of plates or shell composite models where the ply materials are based on smeared or averaged material properties that assume some homogeneous effect, although the layers themselves make the material assembly anisotropic through its depth [2, 3]. The strength of each layer depends on the volume fraction of fiber to the matrix and the orientation of the fibers in that layer. Hence, it is needed to bridge the gap between averaged material properties and computational structural analysis starting from the detailed statistical analysis [39].

Structural sections such as inter-stage structures of spacecrafts are made from diverse manufacturing methods like filament winding, fiber placement, additive manufacturing, or cellular/sandwich composite structures [4, 9, 17, 21]. Conventional sizing methods for these structures maintain the ultimate load limit prior to the initiation of any damage and consider manufacturing and operational defects with adverse factors on composite material properties to corroborate the damage tolerance [15, 28]. Damages such as matrix cracking, delamination, fiber breakage may induce a considerable depression in the mechanical properties and a loss of strength. Furthermore, these damages, which may further cause ultimate failure even unintendedly during the service life of a component/section, may propagate in composite structures and lead to the ultimate failure. More complex methods may be used to evaluate the impacts of defects such as in the form of dimples, but those methods could be implemented in order to assure the validity scope of the structure. Those methods are not suitable for quick sizing issues realized during a typical design cycle to ensure the best sectional and dimensional values by considering damage effects from the initiation of the structural design.

3 Digital Twin Applications in Space Operations

3.1 What is Digital Twin

A digital twin is a virtual copy of a physical system. It can benefit from machine learning and reasoning and simply can be used to create better simulation environment to support decision-making processes, enhance performance, and generate possible improvements. It was the space industry who pioneered the digital twin technology. The US space agency NASA first used digital twin technology, during space missions in the period of 1960s. David Gelernter wrote the idea in 1991, and digital twin software concept was first created by Michael Grieves in 2002. Although the concept was not specific enough at the time, it was suggested that the digital twin should include the physical product, the virtual product, and their interconnections [10].

There are numerous use cases of digital twins. Use cases of digital twins are listed in Table 2.

Digital twins enable more effective research and design environment, can be used to span the lifecycle sustainment of the physical systems, can help mirror and monitor production systems, and can enable greater efficiency throughout the entire manufacturing process. They have potential to benefit engineering, automobile and aircraft production, building construction, various manufacturing processes, and power installations.

Table 2 Use cases of digital twins

Physically large objects	Buildings, spacecrafts comparatively more complex objects
Complex objects	Large mechanical systems, automobiles, complicated machinery
Power equipment	Systems for generating and transmitting power
Manufacturing projects	Helping streamline process efficiency

Table 3 Dimensions of digital twins

Five dimensions of digital twins	
Physical part	Physical system, machine
Virtual piece	Enables the simulation environment and empowers decision-making and control
Connection	Communications and connections between physical and virtual dimensions
Data	Major issue of digital twins, prerequisite for knowledge
Service	Established services

3.2 Digital Twins for Spacecraft Protection

Digital twins support industry with lots of benefits by driving innovation and improving performance. This technology ensures cheaper methods, predicts, simulates, and get insight in a complete system, and enables operational overview into an operation using 3D simulation. The greatest benefits of digital twin technology for space operations are to secure space travel, to improve space shuttles through virtual twinning, and to maximize the accuracy of space surveillance operations. Based on the three-dimensional model, researchers proposed that a complete digital twin should contain five equally important dimensions. These dimensions are physical part, virtual piece, connection, data, and service as summarized in Table 3 [29].

Virtual twin part enables the simulation environment and empowers decision-making and control of the physical system. Data are the major issue of digital twins since it is a prerequisite for creating new knowledge. In addition, digital twins lead to new services that can increase the use, solidity, and fertility of an engineered system. Finally, the connector associates the physical system, the virtual twin, the data, and the service. In such engineering applications, compared to the conventional production system, the digital twin in a broad sense has many distributed smart devices, a more complete information system, a more perfect data collection and transmission system, and a more comprehensive product monitoring and control network. It can realize systematic, comprehensive, and real-time control of items and optimize all activities within the system. It can meet the potential demand of product management throughout the lifecycle; hence, product design, manufacture, service, and other product lifecycle activities can be performed efficiently [41]. According to Grieves, if virtual models of physical objects are created digitally to simulate their behavior in real-world environments, the digital twin consists of three dimensions: physical assets in the physical world, virtual models in the virtual world, and linked data that connect the two worlds. Three dimensions of a digital twin are demonstrated in Fig. 1.

Digital twin technology has been providing a new paradigm in data processing, simulation, and engineering research [11]. A virtual object defined in digital space that has a mapping relationship with a real object in physical space in multiple dimensions, including but not limited to geometry, material, functionality is referred to as a digital twin. In an ideal case, any information that could be obtained from inspecting a physically manufactured product can be obtained from its digital counterpart [30].

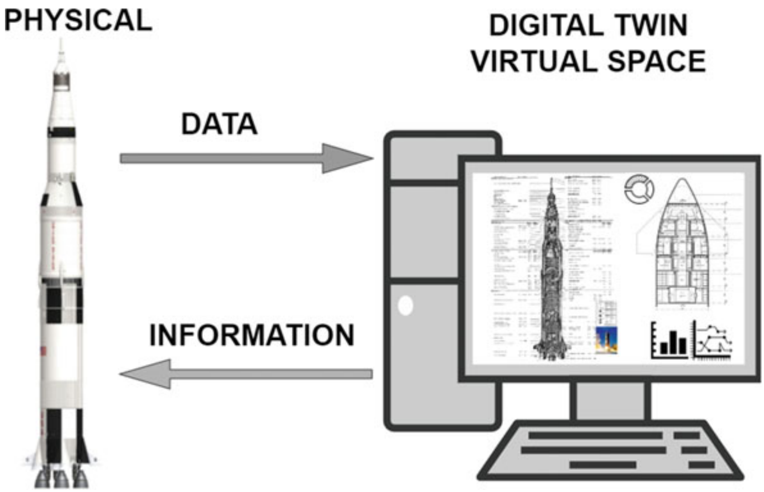

Fig. 1 Three dimensions of a digital twin

It can be represented in the digital world in near real time using feedback from sensors in the system [5]. Hence, the digital model provides valuable results in terms of simulation and analysis, which in turn can be used to control the manufacturing process as well. Due to the rapid development of data collection issues, creation of virtual technology stimulates digital twin technology. With the help of smart manufacturing enhancements, the digital twin brings forth the restructuring of structural life prediction and its management [34]. Digital twin information production process is shown in Fig. 2.

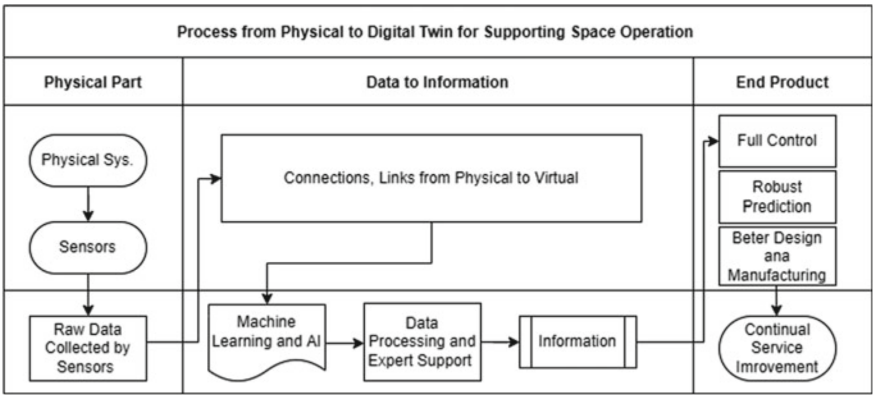

Fig. 2 Process from physical to digital twin for supporting space operation

The widespread adoption of information and communication technologies by manufacturing companies around the world, together with the growth and developments in digital technologies, enables easy integration of interconnected smart components. Devices can be remotely sensed and controlled over network infrastructures, allowing for a more direct integration between the physical world and virtual systems, resulting in higher efficiency, accuracy, and economic benefits [20]. Once the development of information technology meets with advanced engineering technologies, the digital twin comes onto stage including the use of simulation and data acquisition technologies [41]. The system has data-driven, intelligent perception, virtual reality mapping, and collaboration interactive features. However, according to some researchers, evolution of digital twin technology would be identified with the integration of simple coding counting virtual reality interaction [16].

Significant efforts are needed to synthesize, test, and experimentally validate the various component models to create the integrated digital twin. The advantages of creating a digital twin are the core elements in terms of minimizing expensive trial and error optimization to save time and money, shortening the product qualification path, and it has many advantages such as reducing/mitigating defects [7]. The benefits of digital twin technology, according to other researchers, may be reflected as follows. The digital twin product may store data on product state, environmental usage data, operational parameters [34]. It records continuously, and the product in use is monitored in real time. Moreover, users can follow the latest status of the product. The virtual model can simulate the operating conditions of the product in different environments. Thus, in order to control the state and behavior of the physical product (e.g., changing the operating parameters), different environmental parameters and operating behaviors can be combined with health, lifespan, and performance which can confirm what effect it will have on.

Based on real-time data from physical product and historical data, product digital twin, product remaining life, and failures can accurately predict. The digital twin brings together data from all aspects of the product lifecycle, laying the data foundations for innovative product design and quality traceability. It enables iterative optimization by promoting efficient synergies between different phases of the product lifecycle. It shortens the product development cycle, improves production efficiency, and ensures accuracy, stability, and quality [23]. By promoting smart manufacturing, the digital twin increases production efficiency, customer satisfaction, and management precision, while reducing cost in its own way. It also extends the life of products and equipment, reducing the development cycle [23].

Among aerospace applications of digital twin concept, landing gear case could be considered as follows: landing gear mainly provides basic support to the vehicle which consists of shock absorber, wheel, brake system, rotation system, undercarriage that is activated at the time of landing. Landing gears are used to absorb impact energy in order to keep the loads transmitted to the body of the vehicle at a minimum level [14]. During landing, heavy loads are exerted on the landing gear. The landing gear is designed to carry these dynamically changing loads and the impact energy accordingly [31, 32]. Flight control system during landing in flight operation covers items such as displacement sensor, pressure sensor, accelerometer. It acquires data through embedded sensors like temperature sensor and strain gauges. Design documents, user manuals, and a digital map of the field are usually created with models at various levels. Digital twin collects both data from the real vehicle to estimate the landing impact load (e.g., angle and vertical velocity at the time of landing, the speed of the vehicle, the weight of the vehicle) and the data from its virtual copy (e.g., the drag impact and friction coefficient of the shock absorber) since it is difficult to measure. The digital twin is not intended to replace experiments. It would help reduce the total number of tests required for part qualification, minimize defects, and provide structurally sound, reliable parts.

4 Conclusion

Digital twin is one of the most important innovative technologies currently available. This technology is crucial for innovative concepts of vehicle active control systems. Using digital twins guarantees online decision-making by using qualified predictions and real-time optimization. We focus, therefore, digital twin technology on the data-driven machine learning approach for benefiting the space industry. This technology is more dependent on computing manual and experience than conventional methods. According to digital twin, systems can be designed by combining simultaneously variable multidimensional data in problem solving. Digital twin-based spacecraft security and safety systems should ensure impeccable predictions results. The use case of ML techniques also is very important for better simulation and prediction.

When the characteristics of the virtual counterpart are like its physical entity, the data obtained through the neural network in the physical and virtual form of the system can be combined. By using digital twin concept, designers can predict the expected load under severe operational conditions. If the load and strength of the structures can be predicted, the designers can reduce the diameter or length of the parts on the system to be lighter and cost-effective. However, this process must be verified accordingly. In case the component dimensions are changed, simulation-based tests should be carried out on system to determine if the revised component causes damage to physical entity. Thanks to the use of digital twin, virtual verifications could be provided in production, where both reliability and healthy production are ensured. Any sorts of knowledge obtained from examining a physically produced product may also be obtained from its digital equivalent. The digital twin concept is demonstrated to be useful and valuable in the aerospace field.

The benefits and use of digital twin technology in the space industry are presented and summarized in this work. Researchers who would like to work in this field may focus on collection and process of data, the use cases of prediction and ML techniques, and information security, which can be ensured by the use of by new techniques such as blockchain technology.

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Emerging Metaverse

Context Before Technology: The Possible Utopian/Dystopian Elements of the Metaverse with Examples from Great Literature

Ozan Sönmez

1 Putting Metaverse on Its Pillars

The "Metaverse" as a futuristic *phantasmagoria*[1] has been the dominant topic of technology circles ever since the company formerly known as Facebook changed it parent company's name to Meta in October 2021. As a result of this hype, there had been a plethora of books and articles written on the concept ever since. I want to take you beyond and before this hype and connect the META VERSE concept to multiple pillars that should establish our understanding of the future of the metaverse. From the pillars, I will give examples from science fiction and utopian/dystopian literature that the future that will arrive with a virtual world and metaverse is actually here today and the train has already left the station to arrive at a station where life will be experienced quite differently than today.

Metaverse is seen mostly as a domain inside or adjacent to the web, software, and technology. However, as discussed in detail in multiple papers [2] and represented in Fig. 1, technology cannot be left alone in its domain without the proper historical contextualization. Much like the internet has not only been a limited technological phenomenon and its inception, wide adoption, and expansion had a profound impact on business, every type of human relation, and general societal pillars like family, religion, culture, and ecology, Metaverse has the potential to become a transformative force post internet era.

[1] See Merriam-Webster [1], according to the dictionary, the word has the following meanings: (1) an exhibition of optical effects and illusions. (2a) a constantly shifting complex succession of things seen or imagined. (2b) a scene that constantly changes. (3) a bizarre or fantastic combination, collection, or assemblage.

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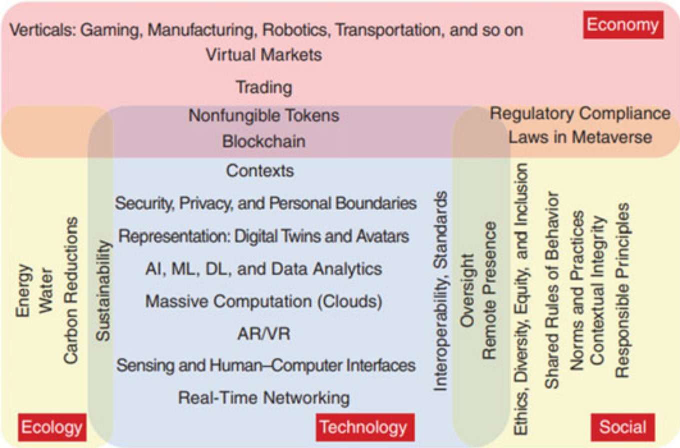

Fig. 1 Informal metaverse architecture [2]

Metaverse is defined from a purely technical standpoint "…describes a hypothetical synthetic environment linked to the physical world that can be accessed using a virtual reality headset, or an augmented reality goggle, enabling one to visualize a virtual environment and create an enthralling experience" [3]. However, when described from a broader perspective is the next bridge between relations and perceptions that humans have value for ages like Philosophy, Religion, Intellect, and Time.

1.1 Pillars of "Meta"

The term Meta is an interesting one. It creates a shape-shifting effect depending on what it is used before. For example, we use morphosis, which mean a change of form, but *meta*morphosis brings the quality and quantity of the process of change to a new level. Statis means stability, whereas metastasis means a stage beyond stability. The same applies to physics and *meta*physics. So, the Meta as a term simply elevates and reinforces the concept "beyond" its original stage and meaning [4]. We can try and understand this stage of being beyond, by using other associations that have similar quantities and associations.

1.1.1 Philosophy

The first pillar of our understanding of the "Meta" part of the metaverse should include the deep history of the search for the meaning of human existence. Not to get into the technicalities and history of philosophy, we should nevertheless include the search for meaning and existence by homo sapiens to uncover the deep impacts and questions the metaverse will create. Simple questions that modern philosophers started to ask long before the technical possibilities of the metaverse are: "Where am I (What am I) if I exist simultaneously on both the physical and virtual worlds? Can my "soul", if it exists, multiply in two places at the same time? Can my existence duplicate itself infinitely virtually? Which one of me is more "real"? The future discussions on these and many more questions will contribute to the *reason d'etre* of our virtual selves and therefore are required to be involved in our building.

We must not forget that these perspectives on philosophy must account for both spheres of influence on human societal development: the Western world and the Eastern world. "The dialectics of philosophical Daoism may further provide a conceptual framework through which to view the metaverse, both in China and abroad. Overall, the perception of the metaverse may be shaped and influenced by Chinese philosophical concepts related to space, being, time, relativity, identity, and the body" Warner [5].

1.1.2 Religion/Divinity

After philosophy, the practical elements of life on the metaverse will be associated with and seen through the eyes of religious beliefs. One way or another, either by prevailing established monotheist religions or by man-made belief sets (like humanism), the discussion of metaverse will spark curiosity in the domain of theism. The perception of the "body" reflected as a mere transport shell to the sacred "soul" in many religions, the dualism of "this life and afterlife", "heaven and hell", brought about by many belief systems around the globe will need to involve various interpretations that are required by the emergence of metaverse as a way of life. These conversations will need to go deeper this time compared to their initial interactions at the beginning of the internet age because this time we are not just going to be agents of actions of an anonymous alter ego, keeping the original person accountable, but an autonomous actor existing and acting through a self-configuring figure with the use of personalized Artificial Intelligence.

The concept of God as the almighty creator of this physical world may be at odds with other entities now playing God in virtual worlds as more and more people will immerse themselves into possible worlds of sin made available with wide adoption. Those who are indifferent to Metaverse are pointing out the balanced benefits of the internet in bringing larger numbers of believer communities in the age of technological advancement. Especially, during the pandemic, the strict perspectives on the necessity of conducting Sunday Church or Friday Mosque congregations had eased and remain eased in most communities. When believers see the places of worship inaccessible, they moved on masse to the internet sermons and still did feel connected to their beliefs and the promises of a rewarding afterlife. Jeff Reed's question "Who is to say that God is not working within the metaverse in order to grow the kingdom"? Rose [6] is a pretty accurate expression of those in favor of any technology moving into the societal domains. True belief is independent of gimmicks, and therefore, anything that has the potential to create mass impact will benefit the believers and challenge those who have diverted from the ways of the true path. There are already movements that have started to call for a placeless practice of religions with hashtags like #hybridchurch and #phygitalchurch.

1.1.3 Intellect/Intelligence/Consciousness

The last pillar of the META elements of the new emerging virtual reality first world should be based on our understanding of the intellect and consciousness. The simple principles of evolution had not been enough to explain the complexity of human consciousness. Neuroscience had been piecing out the functions of the brain piece by piece and connecting the physical infrastructure of the brain to the emergence of thoughts and the mind as well as the actions of the body; however, little progress had been made. Even the comparatively tiny mammal brains had been proven difficult to map and manage. Although there are experiments that managed to transfer data from one mice brain to another and allow them to get out of mazes, the human brain is a much sophisticated maze [7]. Where does decision-making happen? Where do emotions arise from within the mind? How do our virtually active intellect and Artificial Intelligence modeled after our self-impact the second lives we will have in the metaverse?

Artificial Intelligence is at the core of the whole metaverse concept. There cannot be a single governing body to decide on all the behavioral risks of a possibly multi-headed un-governed metaverse. Even remembering the debate between Joe Rogan and Mark Zuckerberg [8] makes it clear that moderation in today's social media tools is difficult to handle at scale. When the metaverse goes to scale, the only tools available to manage crypto fraud, virtual identity theft, and NFT copyright issues will be determined by how the algorithms are functioning. These algorithms will not remain in the background for so long. The non-player characters (NPCs) that are ever abundant in the movie adaptation of Ready Player One and Ready Player two, gave us a glimpse of life in the virtual world.

1.2 Pillars of the "VERSE"

When the universe is defined as "all of space, and all the matter and energy that space contains. It even includes time itself and, of course, it includes all beings (you)". Metaverse can be defined as "A collection of all the virtual universes that we will be able to create, enter, exist and destroy" [9]. From these lenses of description, we have to expand our understanding to explain the pillars of the universe to be included in the metaverse as well and uncover the right questions.

1.2.1 Time and Other Dimensions

It may be puzzling at first to those who learn that the official definition of a "second" is only agreed at the 13th General Conference on Weights and Measures.[2] It does not mean that time did not exist before, and it was calculated by man; however, the concept of time as a sequence of things happening one after the other is a critical pillar for our understanding of upcoming virtual existence. When the time was proven to be relative to the acceleration of the observer, revisiting all the Newtonian concepts of absolute time, brought upon a new understanding of the universe around us. How will time move within the virtual world? Will days, months, and years have different cycles in the metaverse, much like they are calculated differently in other planets or will the metaverse prove to be timeless blending past present, and future all in one, or be motionless?

1.2.2 Space

The discussion about space is an integral part of the time pillar and questions we have raised in that segment are also valid for this segment. Our interaction with the physical world and its three dimensions has clear boundaries. Adding time as a fourth dimension to our physical existence does not change the boundaries it feeds right into the Cartesian way of thinking established by Descartes. In fact, the principle of Descartes is the closest ally any discussion on Metaverse should include. The struggle to understand where the body (physical) and the mind (metaphysical) interact and how consciousness arises from the interaction had been a key research area for Cartesians [11]. Understanding the individual and the indivisible mind will propose a great challenge in our search for the impacts of immersing ourselves into the Metaverse where the body is divided into being in the real world and in the virtual world.

1.2.3 Species

This is probably where the physical and philosophical discussions of time and space will give way to a solid discussion about where we will need to focus on and predict from the known realities of the homo sapiens: Evolution through Natural Selection via Reproduction. Even before Charles Darwin and Alfred Russel Wallace[3] turned evolution into a theory with scientific evidence in the nineteenth century, mankind had been trying to understand how we "became" what we are. Before modern humans

[2] See *Caesium standard* [10], the second is the duration of 9192631770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium 133 atom.

[3] See National Geographic Society [12], Wallace has played a significant role in building the theory of Evolution but goes mostly missing from in the general public's view compared to Darwin.

began believing that various gods created earth and humans from different ingredients, philosophers like Anaximander had reached the conclusion that we, as a species, must be coming from some other animal. The simple reason was that human babies were born completely dependent on others to take care of themselves for a very long time and could not survive independently. This led to the conclusion that other animal species (especially, fish) whose babies can have simple functions to survive on their own should be our ancestors [13]. A species that would require so much care could not have survived in nature for this long to grow into an adult human; therefore, we must have other origins as a species.

This is where it will get interesting in the Metaverse: as gender identity becomes part of a political and social agenda severing its ties from the biological sense, how will humans experience and organize sex, reproduction, and thus evolution? Will there be sexless generations growing without the need to establish romantic relations in real life and engage in acts of reproduction? As technology evolves, will our virtual self also reproduce and evolve or will the metaverse be a place where we can have our alter ego live the fantasies through our physical body?

2 What Will Get Built on Top of the Pillars?

Now, we have our footing and baseline questions through the pillars of Meta (Philosophy, Religion, Intellect) and Verse (Time, Space, Species). We are going to use these questions to hypothesize how the Metaverse might change the interactions between mankind and various elements of life built on these pillars. These will be:

- Tangible realities like corporations, nation-states, ownership of assets.
- World views like liberalism, socialism, totalitarianism, and religions.
- Emotional states of being like happiness, freedom, security, love, and sex.

We will trace how these realities, religions/belief systems, and emotional states were portrayed in utopian/dystopian and Science Fiction genres and propose that how they will impact us when a virtual world prophesized by the emergence of metaverse emerges.

3 Following the Breadcrumbs of Utopia and Dystopia to Metaverse

We will build our base estimations on what the Metaverse will include, exclude, build, and destroy in our future lives, by following the Sci-Fi and utopian/dystopian genre. As an avid reader of the genre, I take great pleasure in using the imagination of the genre's legendary names: Ursula K. Le Guin, Aldous Huxley, George Orwell,

Table 1 Author names and their birth and death years

Author name	Birth and death years
Yevgeni Zamyatin	1884–1937
Aldous Huxley	1894–1963
George Orwell	1903–1950
Ursula K. Le Guin	1929–2018
Kim Stanley Robinson	1952–
Neal Stephenson	1959–
Ernest Cline	1972–

Table 2 List of books and their publishment years

Book name	Publishment year
We	1920
Brave New World	1931
1984	1949
The Dispossessed	1974
The Ministry for the Future	2020
Snow Crash	1992
Ready Player 1 & 2	2011 and 2020

Yevgeni Zamyatin as well as its upcoming thought leaders like Neil Stephenson, Ernest Cline, and Kim Stanley Robinson (Tables 1 and 2).

3.1 Snow Crash: The Nation-States and Corporations in the Metaverse

Neal Stephenson [14] coined the term "metaverse" in his book *Snow Crash*. He borrowed the term "avatar", which represents the actual players' online and virtual self from game makers F. Randall Farmer and Chip Morningstar, both terms are now commonly used in describing the distinction between the real and virtual. Without giving too many spoilers about the book, we will dive into the most novel idea in the book that we should expect to be included in the future of the Metaverse: the blended Nation-States and Corporations.

In the book, the land of the current USA (and possibly other nations) is divided among corporations and mega entities rather than the sovereign and united nation-state of the USA. Large swaths of land are owned, managed, and operated by independent and semi-autonomous corpora-states. There are still reflections of historical national and racial elements in these corpora-states; however, their actions are planned and executed in the best interest of their subscribers (not exactly citizens) by the owners of these entities. Democracy does not seem to be working in the sense that elections and the free will of the people are not reflected in the administration; however, the individuals of this quasi corpora-state are free to choose to remain a subscriber and value creator or move to another part of the world.

This idea of mega corpora-states is not new, but the interactions between the individual and these entities are explained in detail in the book making it unique to read. One might find the idea that corporates issuing visas, managing borders, and exploit resources of the land ludicrous through experiments. The metaverse is owned and managed by private establishments which may also be a little off-putting to think about considering the massive infrastructure that needs to be operated, but we are actually not that far away from this reality of massive corporates managing the majority of the world's resources and future.

The mega companies of today, usually referred to as GAFAM in the West: Google, Apple, Facebook, Amazon, and Microsoft, are managing significant portions of e-commerce, advertising, entertainment, software, and hardware businesses. No startup, large corporation, or nation-state for that matter is free of their impact and decisions. These private entities, which have a limited number of decision-makers, can inflict massive economic shifts, create, or enable political directions and influence the lives of billions of people around the world on a scale not observed at any time in the history of mankind. The net worth of these five companies is more than 4.5 trillion US dollars and the net profit is around 320 billion US dollars [15]. To put the numbers in perspective, if the net profit can be considered akin to GDP of a country, the bottom 79 countries of the world according to ranking per GDP by the World Bank reports have a cumulative GDP of 318 billion US dollars [16]. Any of these companies from the most profitable Apple to the highest revenue-generating Amazon could at any day acquire a country with its loyal citizens. One wonders if they have not purchased any nation-state so far because it would create more bureaucratic issues and reduce productivity or because they can control more legislation power by just providing critical economic incentives and building relations with countries and states enabling them to pay less tax (Fig. 2).

Whatever the reasons might be now, it is no doubt that these large companies have only preferred to remain private entities because of today's context, even though they have amassed fortunes to be able to do so, if and when they choose fit. That is exactly what *Snow Crash* builds upon and gives us an imaginary world where corporations reign supreme. In a world that is expected to become more connected through the lenses of the metaverse, we must remember the possibility that nation-states, some existing for hundreds of years where others are younger, can be turned on their heads to be the mediators of corpora-states.

A more eastern look to fortune building is also necessary to evaluate this possibility. What GAFAM is in the West becomes BATX in the East: Baidu, Alibaba, Tencent, and Xiaomi. To make it easier to contextualize you can assume, Baidu is Google's eastern reflection, Alibaba is Amazon's, Tencent is Facebook's, and Xiaomi is Apple's. These corporations are privately owned on paper but are highly politicized and operated with Chinese national interests in mind [17]. The Liberal and Communist belief systems (one might go as far as Yuval Noah Hariri to call them religions) have created equally strong influential powerhouses. Where the West has

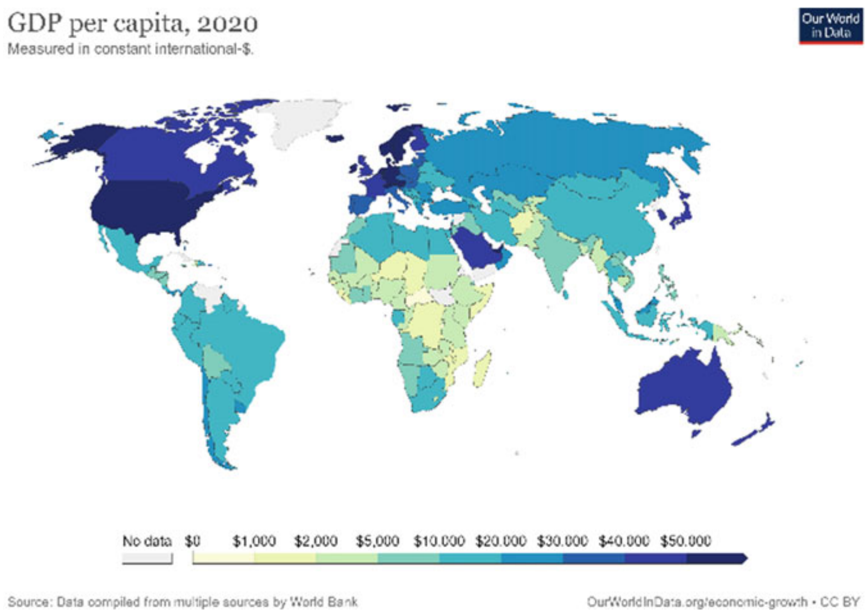

Fig. 2 GDP per capita by countries, 2020

taken advantage of the fall of the USSR to push its liberal agenda to most of the world, China has built an economic miracle by taking only the necessary elements of liberalism without adopting its cultural individualism but remaining a collective idealistically socialist entity. Therefore, the nation as a whole still possessed a much more integrated influence than the West on how the next virtual world will be left to unfold in its society. Nevertheless, the current authoritarian surveillance mode that we will touch upon in one of the next chapters is a clear indication of how China will manage its transition to the virtual world.

3.2 Ready Player One and Ready Player Two: The Connected Metaverse Where Living Becomes Fully Virtual

The challenge for me in writing these sub-sections is to avoid giving a lot of spoilers for the reader who might have not read the *Ready Player One* [18] and *Ready Player Two* [19] but rather watched only the Spielberg Movie. Without giving specifics of the script and scenarios, I would only say that readers might wait to see what happens in the Oasis next.

If you have neither read nor watched the movie though, I need to give a bit of a context. In the year 2045, humanity is either living on stacks, trailers built on top of each other, or in high-performing cities with excellent connectivity to the

Oasis, a single dominant metaverse, created by a company (Gregarious Simulation Systems) built by few people (James Halliday and Ogden Morrow). Everyone is prioritizing their virtual life over their reality, to the point of spending fortunes in gear, time, and intellect. It leads to many people owing to one of the Internet Service Provider's (ISP's) Innovative Online Industries large sums of money and time. These two companies connected back to our previous chapter, act and operate like quasi-independent corpora-states with their own infrastructure, defense, and development arms. Long story short, the social challenges that are created with the total immersion in a virtual world are taken into a new level and multiplied because of a competition to win control over the Oasis.

The books have visualized how critical elements of the future of living might change: Living standards, Education, and Entertainment. One of the transformations that the book prophesized was the elimination of physical teaching and learning spaces we call schools today. It gave a pretty accurate reflection of what happened to education all over the globe during the covid pandemic. Billions of people have realized that if you can overcome infrastructure problems (connectivity) and income inequality issues that limit access (to hardware) and educate the teachers to design and deliver courses remotely, there is a great incentive for students to study from home in a virtual environment. The critics of the transition to virtual or hybrid models fall short of understanding how the next generation would want to learn and what learning is at the first place. I will not advocate for this transition under the current circumstances; however, social and physical interaction that is cherished by educators needs not be in a class setting to make young adults learn better. In a world that should strive to provide growth opportunities to all kids regardless of the place of birth, race, religion, or gender, it is very easy to advocate for a better distribution of opportunities via online and virtual means globally.

We might see the Oasis only as an entertaining idea with limited real-life examples to masses, but we would be mistaken. Today, this virtual shift in entertainment is already happening in the virtual world and it is called e-sports. In 2018, the last tournament of League of Legends before the pandemic hit the world was watched by almost 100 million people worldwide and by 44 million people at the same time, making it one of the most viewed live events in entertainment history [20]. In comparison, Superbowl, the American Football finals, who attract only an American Audience and thus have much less impact on shaping the global attitude, has had very close audience numbers [21]. When you consider that the audience is not watching the real people behind their computers but how their avatars perform, the total digital virtual immersion capacity becomes apparent.

A key element of this virtual world is not just how the individuals play and give life to avatars, but how the non-player characters (NPC's) interact with the human-controlled characters. The sheer size of the metaverse created under Oasis required self-sustaining, self-regulating avatars that do not even have to operate under Asimov's "Three Laws of Robotics". Oasis is representing real live, with good and ill-intentioned human players, as well as non-human counterparts. It actually is the real trick for us to understand and plan for in order to build the actual metaverse and predict the scenarios. How will we interact with an almost organic life-form existing in the complicated algorithms of AI? How will the ebb and flow of evolutionary principles impact the development of the Oasis counterparts and NPCs in the real world?

We are already experiencing a shift toward AI, which makes decisions for us in the real world whether that is represented with self-driving cars or optimized ad placements. We are not yet interacting with a "virtual life-form" and there is still time; however, as we will talk about a species' reproductive choices perspective soon, the reality of virtual immersion is here, now, today.

3.3 Brave New World: Is the Metaverse the New Soma?

Aldous Huxley (born in 1894) started writing the *Brave New World* in 1931 when he was 37. He had witnessed wars and societal change in his homeland, England. The influence of war and the following post-war decade of depression and transformation seeded in him the creation of a model London where science has taken over in the future [22]. Trying not to give too many spoilers, one might argue that, in *Brave New World*, Huxley [23] has predicted most of what we are experiencing in today's world. Technology has enabled a perfect ground for societal change in the last two decades with the widespread growth of connectedness primarily via social media tools. New generations are experiencing a connected loneliness as well as an ever-growing purposelessness. What some people call as the "snowflake" generation, this age of young individuals always wants to have more, keep searching for their true selves, are raised with the idea that they are unique and continuously protected from any harm or hardship. They are becoming more addicted to the façade of pleasant experiences they consume on social media. Sex has almost become in demand with the rise of hookup applications, and there seems to be less time to build meaningful relationships. Marriage keeps getting delayed, career expectations of women and men supersede the establishment of families, and childbirth is put on hold if not altogether dismissed in the modern world. The impact of lockdowns over the past three years during the pandemic had only a temporary and limited positive effect for birthrates in Huxley's homeland, but it is probably not enough to put the birth rates above the accepted replacement fertility rate of two [24]. People are living longer and keeping their health under management for a longer time with anti-aging treatments both mentally and physically.

What Huxley described in the *Brave New World* is an almost perfectly accurate reflection of this status. In *Brave New World,* people are kept "happy", with medication they do not age, they are given a purpose and job to fulfill by the genetic design of their brain functions in incubation and reproduction centers (hatcheries). Sex is a casual act to be enjoyed by anyone and everyone at any anytime, in the new London, "Everyone belongs to everyone else". Marriage, fatherhood, and motherhood are truly extinct and despised. Partners shift and no one has a deep connection or a ceremonially sanctioned relationship.

Life in the *Brave New World* is a by-product of the perfectionism of two leading figures: Ford and Freud. Fordist production methodologies created the perfectly functioning material world, and thus, Ford is revered almost like a messiah. Freud is also an equally critical character. Where Ford perfected the design of the material world of production, Freud has perfected the design of the spiritual world of character and perfected conditioning for human caste systems. Both these predictions have almost been 100% accurate, and what led to today's economical ideals and liberal philosophy is the general pursuit of growth through economic efficiency and control of the mind through drugs and social media. In this sense, our world is eerily like the one in *Brave New World*.

What has been missing from these predictions is the connection of Metaverse to what is about to come. What we lived through over the past 20 years of the twenty-first century was still mostly analog and partially digital but not yet virtual. Will the next generation of technologies to be developed around the metaverse provide us the tools enabling us to experience the perfect utopia of the *Brave New World*? Has the pandemic accelerated the transition to more virtual worlds, increasing the digital footprint of technological innovations to conquer the last habitats of the analog world? The transformation of healthcare, education, entertainment and mostly service sectors from their analog versions to their digital twins has created a fertile ground for more data-driven solutions to be created. Caste systems that we did not realize existed to this extent were made more visible to us during the pandemic: global nomads who can work anywhere in the world with their laptops run supreme, whereas production workers were forced to work as if nothing has changed and service sector suffered great losses and faced unemployment with the lockdowns. Will the metaverse deepen this divide in the workforce, increase the virtual availabilities to find pleasures and avoid pain, and reduce the ability of humans to step away from the habits of social media consumption and focus on things like love, family, and children?

For sure, the utopia of the New London (World State in the book) is appealing to some already, a world that excludes pain from life and offers pleasure on demand, a world where everyone is perfectly manufacturing physically and mentally. Let us hope that humanity will remember that hardships and crises give meaning and new potential to innovate in life and that the Metaverse will not be a Fordist/Freudian tool to engineer society further socially and chemically.

3.4 Bringing in the Big Guns: What if Metaverse Becomes a Tool for Authoritarianism

The fear is very valid. The outcry of the tech world, except for people working in Meta/Facebook, had almost been unanimous, and Metaverse *should not be* owned by Meta. Even Keanu Reeves, the famous lead character in the Matrix series, recently vocalized the same concern in an interview [25]. You know something must be off when there is almost a common enemy in the tech world that is targeted by so many different groups. What that "something" is clearly articulated by experts: the data owned and influence created through that data should not be owned by a single company without the necessary checks and balances provided by regulators. The fear is very justified, the big tech has been reported and investigated many times for breach of personal data, and even the presidential elections in the USA had been tilted in favor of a candidate by spreading targeted misinformation to swing voters. If big tech can play a role in mass manipulation to swing votes and convince us to buy goods and services, can it also be used to social engineer a society, control dissidents, regulate the flow of information, and avoid truths while posing to have a neutral capitalist agenda?

The same fears were in the minds and hearts of many writers, most notably in the minds of Yevgeni Zamyatin (Born in 1884) and Eric Blair better known as George Orwell (Born in 1903). Both Zamyatin's and Orwell's worlds had been shaped by revolutions and World Wars. The post-war and revolutionary catharsis of WWI in Russia have shaped Zamyatin, and the post-war and revolutionary catharsis of WWII England have shaped Orwell. *We* [26] was published in 1924, and *1984* [27] was published in 1949. Both are set in a world where dissent and differences are not tolerated and cruelly "cured". Both are set in world under constant surveillance through new technology. All are under the control and mercy of absolute rulers, Benefactor in the *We*, and Big Brother in the *1984*. The expansionist policies of both the One State (in *We*) and Oceania (in *1984*) are authoritarian and ruthless, and they create nothing less than carnage. To be honest, they are the mostly the same novel with minor changes in details and time perspective. Orwell would probably not have written *1984* exactly in this fashion, at exactly these years, unless he had not been given a task to write a review of, *We* in the Tribune in 1946. The same similarities had also been noticed and reported for Huxley as well. Kurt Vonnegut had not been shy about it, when he said, "*I cheerfully ripped off the plot of Brave New World, whose plot had been cheerfully ripped off from Yevgeny Zamyatin's We*" [28]. In short, the authoritarianism and the realities of authoritarian policies and practices, which we will focus on here, as a utopian/dystopian element is well established into the genre mostly through the work of Zamyatin, are followed by Huxley and Orwell.

As *1984* had been a much more popular read, I will not shy away from pointing out some similarities between the fictional world of the book and the real world. The connection is not hard to make between what the worlds depicted in the shape of One State/Oceania and the present-day USA/Great Britain/China. We do not need Hollywood scripts and movies like *Black Mirror* or *Person of Interest* to visualize the realities of the surveillance mentality. China is becoming a techno-state with the help of super applications, tracking every move, purchase, travel, and communication. They managed to increase their superiority and efficiency during the pandemic with CCTV cameras integrated with the mobile networks tracked each infected citizen and sent stay-at-home orders. London is fast becoming the world's number one city in the West, in terms of CCTV networks per capita, and all set up and operated under the pretense of national security against terrorism. The USA was (probably still is) on its way to perfecting the surveillance system before exposed by Edward Snowden of the NSA's strategy and technology.

Not much has changed in the last almost 70 years about the fears of authoritarian regimes. If any writer now wants to write a follow-up to both novels, they would surely be similarities between the story than and story now. This is one reason why *1984* is almost never out of print, spiking in popularity in the recent years in the USA, where President Trump made a great "bad character" as if he is playing a role from a movie. It is as easy to say "2 × 2 equals 5" and categorize his new enterprise (Truth Social) as "Double Speak".[4] In today's fears, the technology had advanced so much that almost perfection is achieved in categorization, dissemination, and prediction algorithms that identify individuals' deepest desires and fears. This bare fact creates the very fear we talked about in the beginning of the chapter. Both *We* and *1984* have predicted a world dominated by single entities, and both have caused great suffering to its people on a global scale. What makes us safe against the same predictions now? We have much-advanced technology without proper control and governance, and we have masses of people who very happy in giving away their data and decision-making abilities to predictions. What the technology enables the masses to do for free, also create gaps in the systems that can be exploited by state entities and not just private corporations.

Metaverse is promising a deeper connection to virtual worlds where we act more "freely" and create more honest data about ourselves. Wearables not only track our keyboards but also our hormones. Smart tools promise to build more accurate digital twins of us and enable them to operate fully automated in these virtual worlds. We love these promises that come almost free, but with one caveat: you need to log in to your Facebook account to gain access to this promised land. There is no *free* lunch in the world of tech, but today we need to inquire about the price tag, more than ever before. How can we make sure to keep our actual freedom of choice and build what we want to build, say what we want to say, do what we want, and buy what we can afford? How can we make sure the Big Brother or the Benefactor that lurks in the dark becomes visible and we protect ourselves where they become all virtual in a beautifully designed dystopian Metaverse?

3.5 The Ministry for the Future: "Coin"ization of the World Economy for Our Own Sake

The world is in flames. Much like we have seen in the worlds of *Ready Player One* and *Ready Player Two*, the ecological balance has been altered to a point of no return, and now, it is fighting back. The homo sapiens as a species is facing imminent danger of extinction because of climate change. As more and more disasters strike humanity, an age-old institution built to defend global unity during the cold war is now at the forefront to defend global existence during the hot war. *The Ministry for the Future*

[4] See Orwell [27], both are direct references to *1984*.

by Kim Stanley Robinson [29] is depicting a world where what we fear today comes to reality in the not-so-distant future. There is strong scientific accuracy built into the book, a common feature of Robinson's world creation that we also witnessed in *New York 2140* and *The Mars trilogy*. The accuracy of the book and the stories built by the strong characters lead us to the only plausible solution to our "tragedy of the commons", which is basically an old economic theoretical dilemma.

When there is no one in charge of determining who will use which common free resource and how much would be allocated to each, what can stop us from over-exploiting the resource to a point of extinction? If anyone is allowed to graze their cattle in a common pasture, if anyone is allowed to cut a tree in a forest, if anyone is allowed to use the water in a reservoir, how will we make sure the earth, the forest, and the reservoir get enough time to recover? If anyone's self-interest is not limited or regulated by the interest of the common, what stops the individual to take as much as they could? The answer is simple: individuals are selfish and do value the certainty of today more than they discount the value of an uncertain tomorrow.

The result of the dilemma is obvious as the name suggests: "Tragedy". The pasture, forest, and water are exploited to point that they cannot renew themselves. The practice hurts the future generation's ability to enable sustainable production and predict or continue economic activities, and most of the time population is forced to abandon the once flourishing scene. One might ask how is this related to Metaverse and technology. Well, the book suggests that the only viable solution to this tragedy would come from coinizing the resources and creating a universally accepted Web3.0-based carbon coin. When all the resources are measured and coinized, much like bitcoin having a finite totality, the total capacity will still be open to the commons but not unexploitable since the price of carbon will be increasing and production will be capped; therefore, no tragedy will be possible. A neat solution to a wicked problem and only possible, actually doable with today's technologies.

Not sure if Satoshi (or Satoshi's) thought that his invention of the decentralized currency would be a possible solution to the environmental crisis, but we know at least he was trying to solve a crisis, the financial crisis of 2009 for sure. While conceptualizing the solution to the endless crisis that is driven largely because of the liberal capitalist growth hysteria, Satoshi has built the foundations of the crypto revolution. The slow adoption of the movement has sparked heated debates, large institutions, and governments ridiculing the attempts to sever ties of official money from their control, where occupy wall street'ers cherished the possibilities of an independent, mass protected, and managed governance of economic realities. Today, the debate is not over: Crypto is here to stay and the adoption pace is increasing against the volatility of the transactional market. The real benefits and impact of the virtual currency generation as well as the cost of mining to energy infrastructure is still discussed, and it may be long before it becomes carbon neutral to mine and transact crypto currencies. However, the true benefit of the movement could be lying in its power in building a common decentralized consensus for goods that are owned by the "commons".

We do not need to repeat the proverb that goes as such: "When the last tree has been cut down, the last fish caught, the last river poisoned, only then will we realize that one cannot eat money". Today we might have a fighting chance using the virtual money and build a carbon coin, to make sure that the last tree is not cut, the last fish remains and last river stays clean. What Kim Stanley has visioned is close to becoming a reality and we just hope we have enough time and move fast enough to give mother nature the time to rejuvenate.

3.6 Transition from Possession to Dispossession: What Does Ursula K. Le Guin Foresee?

I will be doing *The Dispossessed* [30] a disservice by talking only about the elements of ownership and avoiding the details around feminism and anarchism, but we must draw a connecting line for the purpose of the book from the context to Metaverse, and that context is the example of dispossession (of material wealth in Anarres). It is hard to explain the delicate relations that the conflicting neighbors (Anarres and Urras) are divided by philosophy rather than physical borders. In Anarres, you do not have ownership, your time belongs to the society, and you are dispossessed from the stress and preservation of material wealth and freed from the accumulation of goods. The limitations of this sort of arrangement is totally foreign to any of us here on earth. It may even be shocking to think about "not owning" anything for the ordinary twenty-first century citizen. Most of (you) the readers feel closer to life on planet Urras, where the protagonist goes to publish his work. In Urras, where the possessions are prioritized, the protagonist finds himself more lost and in the end returns to his homeland and gets us closer to understanding the underlying principles of both worlds. The operational principles of both worlds had been told by Le Guin without giving too many options either way. In one society, you have possessions; in the other, even the idea is absurd. Let's not connect this to our society today where are struggling somewhere between our versions of Urras and Anarres.

Both in today's liberal capitalist economies as well as in the socialist–communist ones, there are (supposedly) no limits to ownership except for one's own talent, connections, and abilities in theory. This belief is well established in the post-World War and post-cold war eras and is cheered and symbolized by the "American Dream". Working hard to have the bigger, better, larger items is the driving force of the economies of most Western developed and Eastern developing countries. This mentality worshiped and promoted by the baby boomers had been unshaken for many generations until the newborn digitals arrive. This new generation is born with more items that they can use and more entertainment than they can consume with the advent of the internet, online shopping, and streaming. When they had this many alternatives, it is no surprise that a new generation of young adults, born mostly after 2001, has been acting "weird". They do not dream about securing a well-paid job at a hundred-year-old company to give them enough to possess but never enough to break free. They go after "experiences" rather than "ownership". They rent on-demand cars, stay at on-demand houses, share what little they have through online renting platforms, build a side hustle even when they are fully employed, and dream of an eternal early retirement where they will use their skills demanded anywhere on the planet where they can just hop off and nomad into. This generation is valuing social contribution and the meaning of work through helping others as well. They take gap years, volunteer for organizations like "Teach for America" or "Doctors Without Borders (*Médecins sans frontières*)", travel to underdeveloped countries and do back-breaking work, sleep in a tent or in the open air to erect schools, build hospitals or provide relief efforts in disaster zones. They are seeking the meaning of work in helping others and making a direct, observable, quantifiable impact on others, much like Shevek searches for meaning in his work on Abbernay; they search for meaning via volunteering at community farms while using couch surfing. The new generation is looking into the world through their smartphone screens or through silent yoga retreats, and they behave quite differently than their grandparents and parents in many senses. They do not want to work hard to leave their grandchildren secure inheritances, they want to spend as much of their parents' resources by not renting out apartments themselves but moving back to their parents' empty nests, and they search for a gig work to sustain their bare minimum lifestyle.

So, this new understanding of life, prioritizing the meaning, joy, and happiness of the individual without much regard for a career or family should be highlighted. It is happening today, and for most people +40, it seems like a curse from hell. There will be fewer things to be owned but more to be rented in the near future. The "Share, Rent, Recycle/Upcycle" mode for textiles, cars, travel, and many others is going to inflict huge losses to companies selling these items unless they turn their inventory upside down and start operating their own secondhand stores and rental services. The success of the Gig-Economy, as well as the Rental-Economy, had been built around the principles of the decentralized economy and a decentralized system focusing on providing local solutions instead of global ones. Now that all bets are off, one should assume less and less will be owned, and much more free time will become available to not just the Born Digitals but to Baby Boomers as well. As GitHub and Reddit grow their base and many of the open-source players plan to start building Web3.0 versions to encourage share-to-earn models, as mobile game companies (Axie Infinity) start offering games a play-to-earn mode, as browsers (like Brave) are created to share the fortunes directly from advertisers, the people of Annares rejoice.

Le Guin has shown us that what a generation of people who are dispossessed should expect from life and how they will find meaning in their work. What we can predict is that this generation of born digitals will have the potential to embrace the Metaverse and try to make it their own no matter what. They will still need basic infrastructure provided to them; however, they cannot care less about the physical representations of ownership. They will probably own and/or hide in the Metaverse, earn, and spend in the Metaverse while having the bare minimum of three-dimensional tangible products.

4 Conclusion: The Questions that Breed More Questions

We have examined the works of writers that built the utopian/dystopian genre and how these great literary examples touched on a few of the critical aspects of the future (of Metaverse). Humans' relations to religion, beliefs, sex, and reproduction on the one hand and accessing to education, to the means of production, distribution, and money on the other are quite different in these works of art and fiction. All these writers and even more of those who touched upon the subject had presented us with quite different opportunities, risks, and rewards. The technical details of the matter discussed and detailed in the remaining chapters are the day-to-day realities of the tech world which have been treating the emergence of Metaverse (and web3.0) with enthusiasm, criticism, joy, and fear. We do not know how the reality will unfold, but we believe that we must go deeper into the topics by analyzing what was imagined in the utopian/dystopian genre and asking as many questions as possible. We might never know the right answers unless we find the right questions.

We had been witnessed the birth of a lot of micro-gods over the past two decades. Bezos, Zuckerberg, Page and Brin, Gates, Jobs, Jack Ma, Pony Ma, Robin Li are a few critical ones. Most of the time, we want to believe that they were aware of the "playing god" syndrome with the outreach and global impact of the companies they built. The customers and consumers of these technologies were happy to see the internet take off and connect with goods, services, and people almost for free. The next generation of consumers and customers however are more varieties of problems accruing due to the principles and choices of this handful of individuals and their boards. They want a wider if not totally equally distributed and decentralized ownership of data and protection against monopolies. The freedom to choose where to get news, services, and goods and how they would want to be portrayed, profiled, and interacted with is going to largely change as a result of Web3.0 and real-world metaverse applications that will go beyond the land grab and coin trading. It is up to the new generation of customers and founders to build the new realities, whether they will be utopian or dystopian, time will tell.

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Cross-platform and Personalized Avatars in the Metaverse: Ready Player Me Case

Sercan Altundas and Enis Karaarslan

1 Introduction

After the Internet revolution, technological advances in telecommunication technologies increased, and online networks spread rapidly. These advances reduced the cost of hardware; helping computers and computer-related products become more available and affordable [1]. After being used in universities and offices, computers and online networks became inseparable parts of our daily lives as personal computers (PCs). In today's world, we work, spend leisure time, socialize, and learn through the Internet using our PCs and mobile devices. The speed and utility brought to us by these technologies are the reason for their vast adoption. We produce and consume more information every day. We use this data to improve our lives in many ways.

Especially after 2019, during the global lockdown due to coronavirus (COVID-19), we had to change our way of life. Many people who perform their jobs mainly at an office had to adopt a remote way of work. Some products and technology that utilize online work, communication, and education have become much more demanded. And this demand caused a jump-start effect in virtual reality (VR) hardware adoption. Institutions and corporations decided to adopt and test VR work software on a larger scale. 3D work environments with avatars started to promise lifelike gamified digital working environments to make remote collaboration feel more immersed [2].

Machine learning (ML) and blockchain technologies gained popularity and found use in the average Internet user's life. Development in machine learning and image processing methodologies gave us a chance to have fast augmented reality (AR) applications. We can now use AR for face tracking, body tracking, face filters,

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_16

object scanning, games, sport, and other similar applications with the support of better ML models and hardware sensors [3, 4]. Most of these use cases are available through mobile browsers with the hardware/sensor capability of smartphones. Similarly, cheaper, smaller, and more affordable VR headsets are being produced and sold to the average consumer. Big game companies are taking steps to make VR games, an area in the games industry that they hesitated to enter before [5]. The thought-provoking idea of digital economic freedom captured the attention of millions with cryptocurrencies and non-fungible tokens (NFTs). The promise of owning and trading digital goods without intermediaries is became a reality.

In 2021, another subject started to get attention, the metaverse. The resurrection of the idea of a metaverse caused debates about where our digital future is heading. And soon after, many big tech companies unveiled their metaverse ambitions [6]. Mark Zuckerberg made the boldest move by rebranding Facebook as Meta, which became the parent company, and it meant pivoting in this direction to become the pioneer of the metaverse industry [7]. A $10B investment decision by Meta in the related fields followed this bold move. It was a no-way-back move and a big risk that encouraged other established brands and companies [8].

We are at the beginning of a new digital era fueled by all these recent advancements in software and hardware technology. We are augmenting the way we live and adding a digital layer to our real life. The combination of the digital and the real world will be the metaverse at the core. We need entities that encapsulate our digital identity and visually represent us in this digital layer of life. These proxies of our personalities are called avatars. Our avatars persist in the digital world to represent our digital memory and collection of experiences.

At this stage, Ready Player Me (RPM) (https://readyplayer.me), the cross-platform avatar creator for the metaverse, provides personalized avatars generated from a single selfie. RPM users can transfer their avatars from one experience to another without any friction, and developers can easily integrate avatars into their applications with the software development kits (SDKs) RPM provides.

The remainder of this book chapter is organized into six sections as the following: Section 2 discusses the main paradigms and definitions of some terms that are used in this chapter, such as metaverse, decentralization, and cross-platform. The avatar concept is explored, and 3D avatar styles are classified in Sect. 3. The authors describe "Ready Player Me" (RPM) as a case study of an interoperable avatar solution in Sect. 4. The technologies, which enable cross-platform implementation, are given briefly. Section 5 discusses the future of avatars. A summary is given in Sect. 6, which summarizes the main points. The questions and challenges are also discussed.

2 Fundamentals

We start with exploring the metaverse, decentralization, and cross-platform concepts before we dive into the cross-platform 3D avatars.

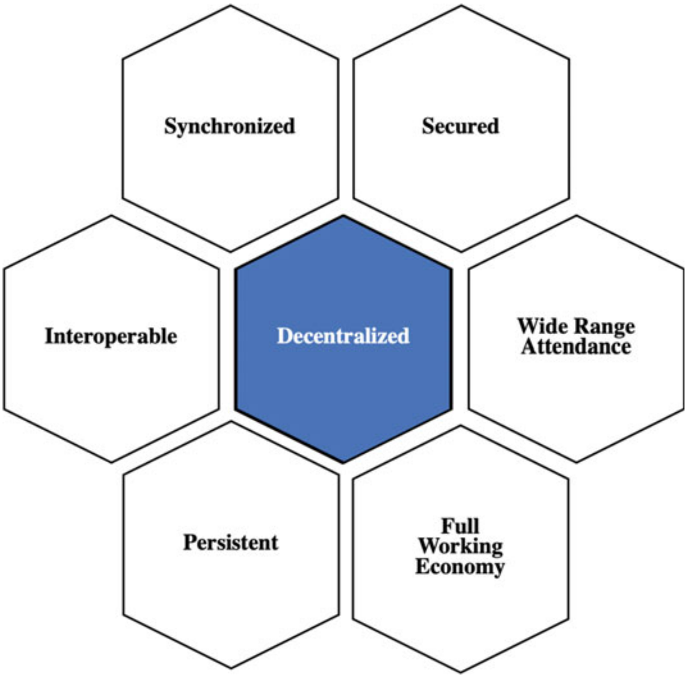

Fig. 1 Metaverse characteristics [10]

2.1 Metaverse

Neal Stephenson, who coined the metaverse term, had dreamed of an open metaverse concept; a single connected universe. The users of that metaverse will be able to interact with each other regardless of the platform they are using [9]. The characteristics of such a metaverse can be summarized in Fig. 1. Full working economy, persistency, and interoperability will require decentralization technologies such as blockchain [10].

There will be several virtual worlds (verses) or platforms, but there will be only one metaverse. It will be a mesh or a net of social and spatial software that connects the physical world to the digital world just like the Internet. In this context, we can describe it like this:

Physical world + Digital world = the Real augmented world.

The digital world in this description is the metaverse, which works as a layer on top of the physical world to complete and augment it with more utility. The need for a metaverse is an evolutionary step in human development. From the ancient times of the humanity to this day, we have been augmenting our bodies and environments to increase our capabilities in different areas of our lives. Especially after the industrial revolution, the speed of technological developments skyrocketed, and the first machinery and later electronic devices made life even much easier. We augmented our ability to communicate wherever we are by using mobile phones. These devices slowly turned into handheld computers which help us be connected and perform many different tasks. However, there is still a barrier between the digital and the physical world. The metaverse is also the ambition to merge these two dimensions.

2.2 Decentralization

Blockchain technology is an immutable registry of transactions which will ensure the integrity of the records and trust. Cryptocurrency and tokens enable one to own and trade digital assets without intermediaries. Smart contracts, the autonomous codes, enable us to create dapps (decentralized applications) and systems such as decentralized autonomous organizations (DAOs).

Metaverse will need a full working economy for the sustainability of the system. The creator economy will ensure the created digital assets to be traded easily. Tokens can be used for such purposes. Tokens are different from cryptocurrencies as their main usage is adding functionality in decentralized applications. Smart contracts can define who can use that functionality and how. Non-fungible token (NFT) is a special type of token which is a unique digital asset. Money and cryptocurrencies are fungible. However, NFT is non-fungible and can be used for identifying an asset uniquely. Specified standards [11, 12] define how NFTs are created on the blockchain. NFT can be traded with customized values according to the rarity, liquidy, etc. [13]. However, the intellectual property rights of NFTs can be misleading [14] and should be used with care.

2.3 Cross-Platform

Software is called cross-platform when it can be deployed and run across multiple different operating systems. This software can have multiple codebases with feature parity for each supported system. This software can have a single codebase with a build and deployment pipeline targeting each supported platform. Cross-platform development or applications are not only for mobile applications. Standalone devices are still in focus (such as PCs, Gaming Consoles), especially for the application of 3D content for performance and usability reasons. These usability reasons are controller support, keyboard/mouse, larger screens, etc.

One app should be able to perform most of its abilities on many different devices to be called cross-platform. It should also be noted that different applications have different needs. As an example, it would not be possible to run graphics-heavy games on old mobile devices. Some old games will need emulators to run on new mobile devices. Some good examples of cross-platforms are Rocket League [15] and Dauntless [16]. These are supported on seven different gaming consoles, enabling users with different devices to play the same game and progress together. These games are graphics-heavy and cannot run on browsers and older devices. However, its category covers larger ground than its peers do.

3 Avatars

Avatars are always on focus as virtual worlds become a part of our lives. Several works have so far studied the different aspects of avatars. The theory of avatar is discussed in [17]. Designing avatars is investigated in [18]. Focus groups discussion is conducted to learn the considerations from the user's point of view. These considerations are based on the appearance, functionality, context, governance, and ownership of the avatars. Another interesting study has discussed the research issues and challenges of 3D social virtual worlds (SVWs) in [19]. Avatar and metaverse subject foundations were given in [20]. The relationship between a person and an avatar is investigated in terms of appearance and behavior in [21]. Another interesting study [22] has demonstrated that the appearance of avatars might have psychological effects on the user. The number of experiments on human subjects in the virtual worlds has increased, and this study [23] addresses it in terms of legal matters. We should find alternative ways of preserving the privacy and reputation of users. A research model for evaluating virtual worlds is given in [24]. This study claims that there is a direct correlation between the attractiveness of the virtual worlds and the identification of its users with virtual communities. Therefore, avatars play a critical role in this identification process. The behaviors and motivations behind the avatar creation in virtual worlds is given in [25]. Protecting the rights and liabilities of avatars is discussed in a recent study [26].

Today, almost all tech giants have their avatar solutions so that they can prepare their users for the metaverse. Oculus by Meta has used avatars in VR since 2016 [27], and later in 2021, they made an update with Meta Avatars used in Horizon Worlds and Workrooms [28] The company also leads research in photorealistic avatars [29]. Microsoft had avatars in the gaming space with Xbox 360 avatars since 2008 [30]. The company has revealed its plans for the metaverse with its new stylized avatars for Microsoft Mesh for Teams in 2021 [31]. Apple acquired animoji face-tracked 3D emojis on iPhone X in 2017 [32], which then turned into personalized animojis called Memoji the following year [33]. Most recently, the video social media platform TikTok entered the space with avatars [34]. In the game industry, Epic games introduced their photorealistic avatar MetaHuman in 2021 [35], which can be used in Unreal Engine. Unity acquired Ziva Dynamics, a company that is an expert in anatomical simulations and lifelike character creation [36]. Roblox as a platform had blocky lego-like avatars since the start, and in 2021, company announced its new avatar system with a set of modern features to make more complex avatars [37]. Many other companies are working on metaverse and avatar-related subjects at the moment. The examples above already exhibit the shift in the tech industry and social game and media software to metaverse and avatars.

Avatars can be two-dimensional (2D) or three-dimensional (3D). Humanoid 3D avatars can be classified according to their body parts such as:

- Head only avatars (Memoji),
- Bust avatars (RPM VR Avatars) with shoulders and hands,
- Half body avatars (Meta Avatars) with head, upper body, and arms,
- Full body avatars (RPM Avatars).

For performance and locomotion-related reasons, some implementations prefer avatars without legs. However, the technologies around avatars are constantly improving. For example, there are some successful implementations and leg-tracking devices [38] that could solve the locomotion problem of avatars [39].

So far, there has been no serious attempt of classifying the avatars in terms of their specific visual styles. Different solutions have used Humanoid 3D avatars in different art styles, which might impact the way the users perceive and relate themselves to their avatars as shown in Fig. 2. We can classify 3D avatar styles as the following:

- Cartoony Avatars: These have low texture and mesh details, and they lack realistic body and head proportions. The representative examples are Meta avatars, Anime-style avatars, and Roblox.
- Stylized Avatars: These have higher texture and mesh quality than their counterparts. The meshes and textures are stylized, and the textures are mostly hand painted. The representative examples are Ready Player Me and Fortnite.
- Photo Face Avatars: These mainly have low to middle-level mesh detail. They try to capture realism by using a face texture generated from a photo. However, this type of avatar looks uncanny, especially when they are animated. This is mainly due to the lack of detail in the mesh and texture. Video games of 2000–2010 are good examples of them.
- Photo-realistic Avatars: These have texture and mesh details with realistic body and face proportions. The representative examples are MetaHuman characters and the video games of 2010 to present.

The uncanny valley is the amount of realism when the observer develops an unsettling feeling toward a humanoid object when it is not convincingly realistic [40]. Yet, the designer can avoid the uncanniness of an avatar with the right style choices [41]. We illustrate the point with a realism and affinity graph (see Fig. 2) to show which style falls into the category of the uncanny valley. RPM provides avatars by using stylized meshes and textures on the facial proportions extracted from the user selfies. This solution aligns RPM avatars in the center of the realism scale with high affinity.

The "Metaverse avatar" phrase has also started to be used in several studies [42, 43]. It is described as the "Manifestation of a user within the metaverse" in [42]. Metaverse avatars should also be cross-platform. We compare such avatars with RPM as in Table 1. RPM avatars can be used cross-platform. They are stylized and suitable for auto-generation. They also have NFT support.

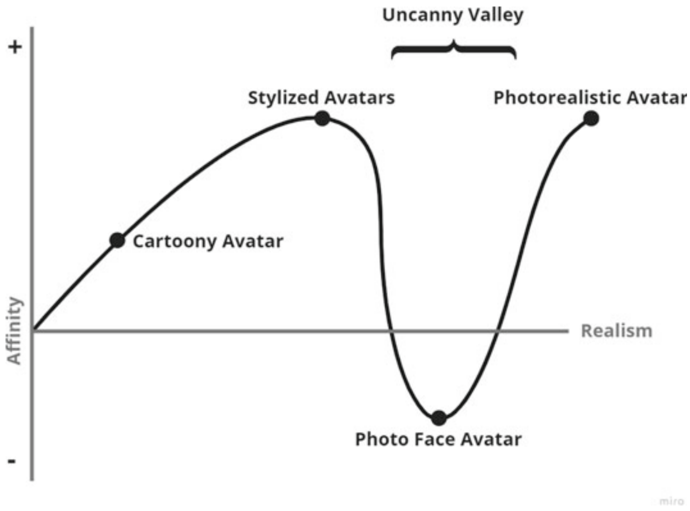

Fig. 2 3D avatars' uncanny valley

Table 1 Comparison of avatar features

Feature	Meta avatars	MetaHuman	RPM
Cross-platform	Meta only	Unreal Engine only	Open
Style	Cartoony	Realistic	Stylized
Auto generation	No	No	Yes
Virtual goods	Yes	No	Yes
NFT support	No	No	Yes

4 Case Study: Ready Player Me

We will show proof of the concept of avatars by introducing the Ready Player Me (RPM) platform. It (https://www.producthunt.com/products/wolf3d#ready-player-me) was launched in May 2020. Ready Player Me is a Web-based cross-platform avatar creator that can create a personalized avatar from a single selfie. This avatar can be used in any games and other applications which can host human characters. The user can download the created avatars in GLB format free of charge. Signed-up members can manage multiple avatars in the system and connect their avatars to partner applications.

RPM architecture is given in Fig. 3. RPM comes with a set of SDKs and integrations for developers who want to integrate it into their system. It can be embedded in applications and games via a mobile WebView, an in-engine browser, or an HTML iframe. This way character creator is delegated to RPM, and once avatar creation is completed, the URL of the avatar model in GLB format is sent to the host application.

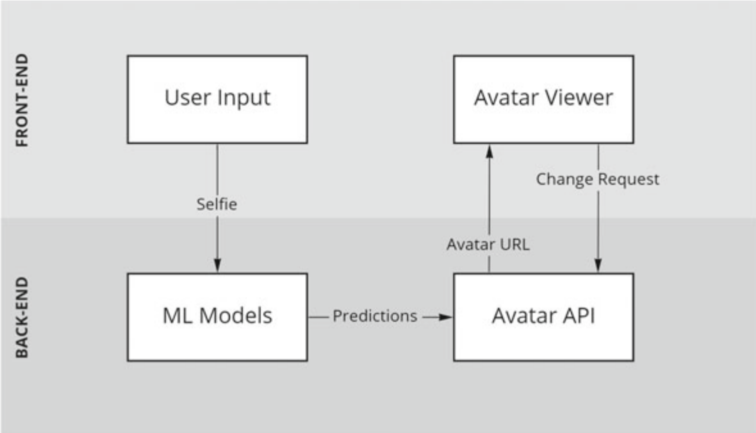

Fig. 3 Ready Player Me architecture

4.1 Cross-Platform Web Technologies

A developer needs to work on the very same application on various tech stacks to make an app cross-platform. So far in mobile application development, the biggest issue has been publishing the same application for Android and IOS markets. Now, it is possible to wrap and publish apps for different operating systems, mobile markets hardware, and consoles with Web Suite-based apps and larger build support options than current game engines. Developers can have a single codebase and different build pipelines then. One of the largest coverage belongs to Web Suite technologies (HTML/JS/CSS). Currently, all mobile devices have a native browser and are connected to the Internet. The same applies to PCs and gaming consoles. Web Pages can be run via WebViews depending on native browsers of mobile devices and can be easily integrated into game engines.

4.2 Cross-Platform Avatars

Cross-platform avatars enable us to use the avatar platform and avatars on various platforms. There are two components: avatar creator and avatar. RPM the avatar creator is a Web site that can run on any platform. It has a native browser with WebGL 2.0 support. An avatar is a GLB model that contains the mesh, texture, bone structure, and material data in a binary file. This file can be rendered similarly on any platform that loads the model.

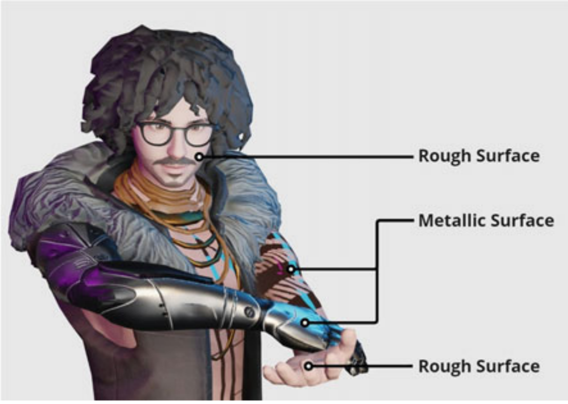

Fig. 4 Physically Based Rendering (PBR)

4.3 glTF/GLB

glTF (https://www.khronos.org/gltf) is an open and free specification for transmission and loading of 3D models and scenes in various applications and platforms. It minifies the size of the 3D assets and shortens the time to unpack and load these assets in runtime. gITF 2.0 released as an ISO/IEC 12113:2022 International Standard [44]. GLB, the binary file format of glTF specification, packs the 3D asset into a single file and serves it in a compact way. gITF performs better in general compared to other formats [45].

One of the most important features of glTF for RPM is that glTF supports physically based rendering (PBR) materials. This ensures avatars visually look the same given similar light and environment settings wherever they are loaded. FBX can also be used to support Phong shading materials. FBX can embed textures in it only with the support of FBX SDK and does not support it by default. Texture and material handling should be done on the platform FBX are displayed and that adds big friction to the whole process [46]. It is easier to develop tools and extensions for glTF as it is an open specification. Development such as texture replacements and merging multiple meshes can be done easily even in a Web backend. This process will not even need 3D software to run on a dedicated server.

Using GLB format to transfer avatars enables the use of interoperable avatars which look the same on any platform they are transferred. glTF specification position sees itself as the enabler for 3D content creation and deployment (https://www.khronos.org/gltf/). Ready Player Me can be considered to be one of the next platforms to carry the flag in making 3D content on the Web a daily part of the Web. As shown in Fig. 4, GLB can contain both reflective and rough surfaces in the same material unlike the FBX format. This is due to the metalness/roughness texture support of PBR. Comparing the same avatar exported as an FBX and GLB loaded in Online 3D viewer in Chrome browser is shown in Fig. 5.

Fig. 5 Avatar in FBX (left) and GLB (right) format

4.4 Avatar API/Render API

Along with the Web platform to create and manage avatars, RPM provides a set of application programming interfaces (APIs) for developers to configure their avatars for their product's needs. When RPM Avatar API is used, avatars can be called with a configuration that in return delivers the same avatar in different Levels of Detail (LOD), texture quality, texture atlas, blend shape options, compression options, and poses.

Not every product needs 3D avatars. There is still a need for avatars as 2D images just like any mainstream product of the current era of the Web. RPM Render API provides quick 2D renders of an avatar to satisfy the needs of these applications and ensure the interoperability of the avatars even in 2D. Similar to the Avatar API, a configuration payload can be sent along with the request to receive a PNG result of the render.

4.5 RPM NFT Implementations

RPM supports NFT (https://readyplayer.me/nfts) in different ways. The company brought EDM musician Deadmau5 mask NFTs to RPM as headwears. The owners of this NFT could connect their wallets to use their NFTs on their avatars and visit all the supported platforms wearing their NFTs. The company also collaborates with a digital fashion company called DressX and designer and NFT artist Pixelord to support their NFT outfits. More and more wearable NFTs will be available in RPM, and this is also how RPM provides actual utility to the NFT projects that integrate with it.

RPM also produced its NFT set Ready Player Me Punks for the owners of CryptoPunks. This provided a 3D avatar body to pixel art image NFTs to be used in digital worlds.

Many blockchain metaverse projects use RPM avatars to provide utility to their projects. RPM shares half of the revenues from the NFTs to the NFT-enabled partner projects to help these projects grow. RPM partners can opt-in to letting their partners use their NFTs in their worlds, which makes use of NFTs in partner projects purely optional.

5 The Future of Avatars

Every year more and more of our lives are moving into digital space, and at some point, we will need our digital proxy to be the point of contact for others. Like how people had physical home addresses, then phone numbers, then email addresses, the social media accounts; everyone will have an avatar of themselves acting as a single source of identity of a person. The avatars will represent them in the metaverse. Users will use VR and VR authentication methods [47] more widely.

Mobile devices and IoT devices on different gadgets are now connected to the Internet. Robots and several different devices will soon join this crowd, and they will offer personalized usage and even will have characters. Avatars will also find their usage on these devices. We will be able to create avatars with more fidelity, detail, and complexity with these improvements.

Avatars will be associated with the identity of the user and will be the entry point of our data in the digital world. We will be able to add, update, share, and remove certain assets into its context. The cloud of information associated with the avatar will probably be kept in a digital wallet. These will have meaning depending on the context of the digital space it visits. Today, we use sports trackers to keep our training information, apps to keep track of the books we read, movies and TV series we follow, places we visited, games we played, and friends we made. Even more, we have digital wallets and other places where we keep our digital possessions such as in-game items or digital gifts we receive. All this info will be contained and owned by the person to whom this personal avatar belongs. The user will share only the required information with the applications. The applications will be able to display and process but not store these data. These will probably be done with zero-knowledge proof (ZKP) based algorithms. Humanity will probably grant separate legal personalities to avatars, will also develop different types of rights and liabilities [26]. This will hopefully bring us to an open and free metaverse.

6 Conclusion

Avatars will be more widely used in our lives as an identity. These avatars will be linked to digital assets and information. As shown in the chapter, "Ready Player Me" made a promising solution that serves as a cross-platform personalized avatar. The interoperability of the metaverse will be possible with evolving solutions like it.

We will see the digital identity and digital assets linked to the avatars in the future. Proper running of the future metaverse will require decentralization technologies like blockchain for keeping digital assets and interoperability. However, we are still in the early stages of this technological progress. The intellectual property rights of NFTs and the rights and liabilities of avatars should also be studied.

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Security Issues in Artificial Intelligence Use for Metaverse and Digital Twin Setups

Utku Kose

1 Introduction

The wind of technological changes has been affecting not only daily life but also people. In especially the twentieth century, revolutionary developments changed the rules and making life practical was associated with the ways for the transformed society. Among the developed technologies, computer and communication technologies had the most influential role for newer technological tools. Today, the humanity faces the fact that the twenty-first century brings intense collaborative interactions of different technologies to build the future. Thanks to rapidly evolving data processing capabilities, daily life objects are now common smart tools, which are helpful to plan human actions. In terms of data processing capabilities, Artificial Intelligence (AI) makes it possible to run adaptive, automated/autonomous systems, which are able to deal with complex problems with even big data [1, 2]. AI has been seen among the most important inventions in the twentieth century, as it is even currently evolving and shaping the future of technology [3, 4]. Except from the AI, advancements in computational resources (in terms of both software and hardware) have resulted to rise of technological solutions such as Internet of Things (IoT) and distributed systems. While IoT has made it possible to use smart daily life (and even wearable sometimes) objects, distributed systems like blockchain allowed decentralized data sharing as meeting with the critical need for ensuring data security [5]. Eventually, every new kind of technological solution made it better to improve data communication and support the real world with the limitless virtual worlds. Although the concept of virtual world is associated with video games and Virtual Reality (VR) of the twentieth century [6, 7], the humanity started to improve the role of human in such virtual worlds, by developing more advanced software environments. Except from multiuser social media platforms for extended communication, a better way for

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E. Karaarslan et al. (eds.), *Digital Twin Driven Intelligent Systems and Emerging Metaverse*, https://doi.org/10.1007/978-981-99-0252-1_17

an entertaining virtual world has been multiplayer games with deep character interactions [8]. However, the digital transformation (for especially business operations) triggered the rise of Metaverse and Digital Twin concepts.

Thinking about the users spending most of their life over the web, the Metaverse is one of the trendiest topics nowadays. By using advanced capabilities of computer graphics (in especially 3D view), Metaverse is the new way of building alternative, virtual worlds where people are able to not only communicate, but also shop, work, and play [9, 10]. The popularity of the Metaverse has increased rapidly in last five years because of intense interest by the society for remote, virtual work opportunities, and the COVID19 period, which forced people to run their tasks over computers. Additionally, advancements within VR and Augmented Reality (AR) and better data security through blockchain affected the way of Metaverse development. The momentum of the Metaverse development was intensively supported by also software giants [11]. As a result, Metaverse has been the solution of a complete, virtual world, which is similar to the real world in terms of people's actions and the corresponding results. In addition to the Metaverse, the concept of Digital Twin has been another innovative way for meeting the real world with the digital one. As corresponding to the fact of creating digital copies of physical components, Digital Twin allows instant control of physical components, by interacting with the digital copies in specific platforms. Such interaction includes extended methods for deriving more information from the present state and predicting the future states [12, 13], that allowed the Digital Twin to be an effective technology for especially industrial devices and factories [14]. However, the Digital Twin has a bigger potential as it can be connected with the Metaverse where people and the objects they interact can be all represented with digital copies. The IoT already shows the potential for creating digital copies of smart devices, via wearables, which is possible for also making connections between people and their digital copies (avatars). Moreover, a possible combination of Metaverse and Digital Twin seems to be a requirement of the society for the future interactive platforms. However, both Digital Twin and Metaverse are intensively subjected to security challenges [15, 16]. Such interactions require use of smart data processing tools, which can be built by using AI. Especially, adaptive processing of the data by Machine Learning (ML) already shows its advantages in today's digital platforms (e.g., social media, video streaming applications, e-trade websites). So, it is just an adaptation to create the smart Metaverse environments where the virtual life can be supported/managed/controlled. However, that use of AI rises another question: how to ensure the security for AI? As it is already known, the latest usage of AI is often associated with malicious intensions (e.g., Deep Fake, AI-generated fake images/data) and AI-based systems are under pressure of hacking possibilities [17–19]. The malicious actions threatening the AI layer may result to hacking of digital twins, data leaks, and break down of the Metaverse platform. So, that scenario should be discussed carefully for understanding the potential threats for the Digital Twin-supported Metaverse platforms.

The aim of this chapter is to provide a discussion for possible security issues in AI use within Metaverse (and Digital Twin)-powered environments. In this sense, the chapter ensures a general overview regarding how AI can be employed in present and future versions of Metaverse platforms and discusses about AI safety risks by giving some solution suggestions. The content focuses on possible usage scenarios for AI and ensures that these scenarios may be under attack of some AI-based hacking actions. It is believed that the chapter will be a recent reference work for understanding the AI potential within Metaverse and Digital Twin setups and running further research for effective defensive actions for well-being of the future virtual worlds.

Considering the aim of the chapter, the remaining content is organized as follows: Sect. 2 provides information about how to use AI for Digital Twin and in Metaverse platforms. The section considers especially potential of ML and intelligent optimization from a general perspective. After that, Sect. 3 discusses about possible security issues caused by AI layer. Following to that, Sect. 4 provides some solution suggestions to deal with the expressed security issues. Finally, the chapter is ended by Sect. 5 where concluding explanations and some future research perspectives are all provided accordingly.

2 Usage Scenarios for Artificial Intelligence in Metaverse and Digital Twin Platforms

It is remarkable that the AI technology has enough flexibility for applying it to different problem domains. As long as the data are the specific material of the digital era, advanced technologies such as AI intensively use the data for ensuring the desired outcomes. In the context of both Metaverse and Digital Twin applications, use of AI gives the advantages of running smart analytics and inferencing to enable a more comfortable using experience for the enrolling users. A comfortable using experience may belong to not only speed and effectivity but also efficiency and automated infrastructure for stability of the actions over the platform. These can be ensured thanks to active use of AI components. Because a Metaverse and Digital Twin blend requires strong connection between physical and virtual world, use of AI is an essential requirement to build a strong virtual platform for the future.

2.1 Components of Metaverse–Digital Twin Collaboration

In order to understand how the AI can be used accordingly in Metaverse and Digital Twin setups, it is better to explain the flow starting from the physical world. Here, Digital Twin plays an active role to replicate the physical components into digital versions and locate them in the virtual scenes. So, a collaboration of Metaverse–Digital Twin is the expected result for the stable Metaverse. However, since Digital Twin is a specific approach developed also separately, the synergy regarding the

Metaverse is considered as a collaboration in today's conditions. That is also a good way to define the roles of AI separately in Digital Twin and the Metaverse.

Thinking about the Metaverse, a proper view for the enrolling components can be drawn by listing technological components and creating architectural overviews for the Metaverse. A survey work by Lee et al. [20] provides a brief list for the essential technological components of a typical Metaverse. By considering that view and also including the Digital Twin, the related components are explained in Table 1.

As long as use of Digital Twin is associated with abstract, software modeling (through connections with physical side), their dynamic mechanisms tend to have strong relation with AI. Actually, all digital contents having connections with the physical components are digital copies (twins) in the Metaverse environment. So, they are somehow software representations having life cycle, interactive behaviors, adaptive features, etc., in a virtual world. Although AI has critical role for their functions, existence of these digital copies cannot be thought without active participation of all the technological components listed in Table 1. In detail, employment of

Table 1 Technological components of a typical Metaverse with the corresponding roles and contributions

Component	Role/contribution
Artificial Intelligence	Ensuring intelligent infrastructure in terms of automated and/or autonomous inferencing and flexible, smart data analytics
Distributed systems	Ensuring data security through decentralized communication, and building safe data storage, usage, and interoperability functions
IoT and robotics	Building interactive connections between physical and virtual worlds. Enabling sensible feedback by virtual components to the physical world side
Digital Twin	Employing digital copies of physical objects so that smart analytics and predictions for future states can be done. Also, mutual effects of physical and virtual worlds can be reflected to each other, thanks to the created Digital Twins
Reality tools	Using VR, AR, and even Extended Reality to design deeper interactivity, and making it possible to usage of advanced visualization capabilities (e.g., holograms)
Computer vision	Supporting the reality tools and ensuring smart scene creations, sensing physical movements (of the user in the physical world), combining GPS capabilities with virtual mapping/localization
Network communication	Ensuring the communication through TCP/IP, IoT, or newer network protocols, performing load balancing and the desired adaptivity in communication share
Interactive tools	Improving users' interaction capabilities via mobile devices, haptic devices, any other kinds of input devices, and telepresence channels
Edge computing	Collaborating with network communication tools and the corresponding technologies to have edge-based, cloud-oriented data management, privacy-preserving infrastructure

Digital Twin and the exact interactivity in a Metaverse are all done thanks to intense collaborations among these technological components.

When the Metaverse setup is analyzed from the functional perspective, Duan et al. define three different layers [21]. These are the **Ecosystem Layer**, which employs events and logical occurrences in the virtual world; the **Interaction Layer**, which is the middle interface for creation of digital content as well as the interactive mechanisms; and finally, the **Infrastructure Layer**, which belongs to the technological components making the Metaverse running. When the existence of users (human factor) is included, these layers were extended to the following seven-layer architecture [22, 23]:

- **Layer 1—Experience**: The layer is for user interactions of playing, working, buying, etc. The main role of that layer is eliminating technical details from user sight and just providing the exact experience.
- **Layer 2—Discovery**: Mostly interacted by third party sides, service providers, and creators, this layer is for providing information, interactive content, messages, etc., to the users enrolling in the Metaverse environment.
- **Layer 3—Creator**: As associated with the Layer 2, this layer employs the creators, who are responsible for Metaverse data creation from static content to highly interactive elements.
- **Layer 4—Spatial computing**: This layer is for the computational existence of visual elements in the Metaverse environment. In order to ensure the desired virtual environment, the layer takes support from 3D engines, specific algorithms to define spatial relations between information of physical world and the data (in terms of everything from user avatars to scenes, objects, etc.) in the virtual side.
- **Layer 5—Decentralization**: Taking the support from distributed systems, this layer carries the decentralized computational technologies such as blockchain, tangle, holochain. So, data security, safe sharing, and interoperability are done accordingly for the Metaverse.
- **Layer 6—Human interface**: The layer is for ensuring interaction between the physical and the virtual worlds. That layer includes use of VR/AR tools, input/output devices, and all the associated tools for making data flow between two worlds.
- **Layer 7—Infrastructure**: The layer corresponds to technological components, which are for sustainable communication.

It is important that each layer of the Metaverse architectures may be examined in detail as long as the Metaverse is a mosaic of advanced technological methods and tools. Defining a Metaverse with layers is actually a logical opening to the user side, for understanding the collaborations among the technological components. Additionally, an alternative view can be done by explaining the technology and human interaction in ecosystems. In the literature, there are several definitions for the ecosystems [20, 24, 25]. By considering them and re-creating a clearer view, ecosystems in a Metaverse can be defined as follows (Fig. 1):

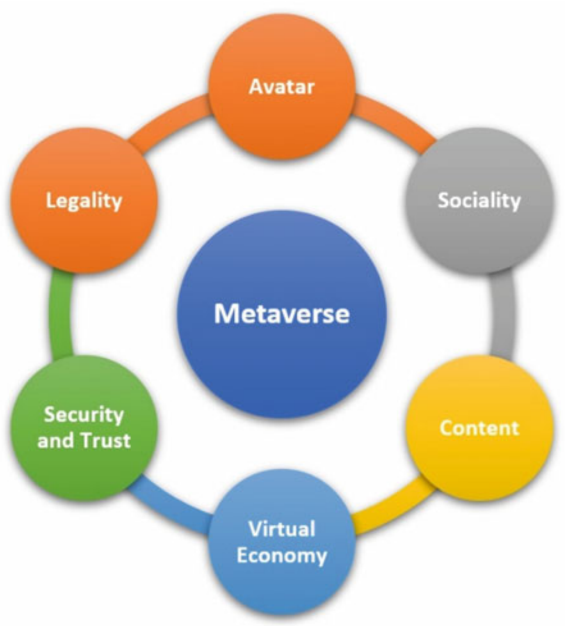

Fig. 1 Ecosystems in the Metaverse

- **Avatar**: The ecosystem where virtual representations and functions are associated with the virtual character (avatar) of the user is included. This ecosystem employs all required interactive connections for replicating the physical person (as a Digital Twin) and making it sustainable in the Metaverse.
- **Sociality**: The ecosystem is running all mechanisms to ensure sociality and communication among avatars in the Metaverse environment.
- **Content**: The ecosystem is running all representations and Digital Twins made for virtual scenes, static/dynamics objects of the Metaverse.
- **Virtual economy**: The ecosystem is making it possible for the avatars to work, buy, and perform actions resulting to economic value.
- **Security and trust**: The ecosystem is responsible for data security, privacy, and the associated mechanisms for ensuring the trust factor in the Metaverse environment.
- **Legality**: The ecosystem is for tracking the legal and illegal actions, which will result to lawful outcomes for both virtual and physical worlds.

All definitions/views made so far point intense use of software and hardware-based actors in a synchronous manner. Such intense use may be done via only advanced and flexible enough, a computational solution. It seems that AI is the most influential and the most effective solution to meet with that. So, AI has the critical role in ensuring both present and future versions of Metaverse platforms. Even today's definitions may be limited to predict the exact potential of AI in the future Metaverse (or maybe new technological versions/concepts following the Metaverse approach). But still, it is possible to explain present existence of AI and the future enrollments by thinking about the promised computational abilities.

2.2 Using the Artificial Intelligence for Digital Twin Components and the Metaverse

AI is used effectively to add smart analytical and predictive abilities to the Digital Twin technology. As long as Digital Twins are for designing software-oriented views for physical objects, user interaction is not about only tracking the objects. By using AI, Digital Twins can allow users to predict the future or ensure autonomous characteristics in the digital world. Of course, outcomes in the digital world will reflect to the physical side, if the necessary setups can be built properly. After inclusion of Digital Twins in the Metaverse, the AI can support the Metaverse mechanisms by expanding the synergy among all other technological components, architectural layers, and even ecosystems. So, AI for the Metaverse is actually the triggering factor for the dynamism in the components of Metaverse–Digital Twin collaboration.

Because AI is the field hosting many methods and techniques, usage scenarios in an advanced virtual environment require hybrid solutions or more generic AI approaches including several pipelines to perform all data processes on the background. However, employment of AI can be explained with some solo ways (blending them is another topic associated with the design of technical details of the AI support). In the default form of the Metaverse and the Digital Twin (inside it), there is a loop between them and the AI, because support by the AI results to a limitless data exchange in the live Metaverse life cycle (Fig. 2).

When a typical Metaverse environment is thought, employment of the AI can be in the following solution ways:

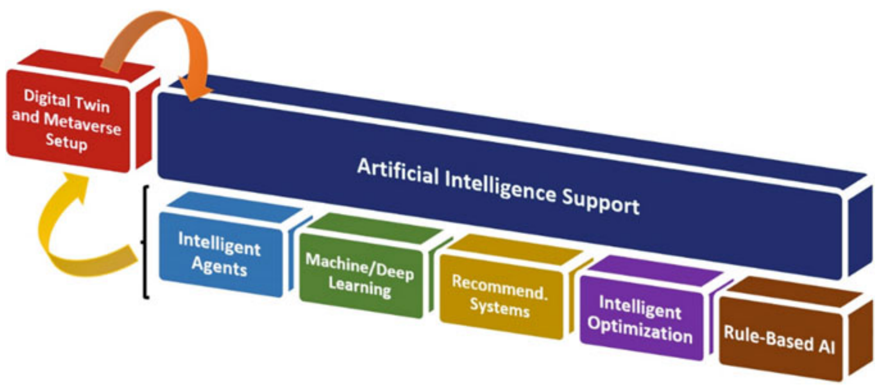

Fig. 2 Using Artificial Intelligence for Digital Twin and the Metaverse

- **Employing intelligent agents**: Metaverse is a world where multi-users and multi-objects are interacting. In order to build the interactivity, user avatars and the dynamic objects (having interaction abilities) need to be modeled from the view of intelligent agent-based modeling. That modeling allows designing virtual objects (including avatars and even bots), which can interact with the environmental factors, perform reasoning, and provide feedback/actions. Use of intelligent agents corresponds to also interactive Digital Twins. Bots, which are supportive AI-based avatars, are built to behave by using intelligent agent approach. As default, multi-agent usage [26] is the only application way for intelligent agent approach existing in the Metaverse.
- **Using Machine/Deep Learning**: Machine Learning (ML) and its current advanced version, Deep Learning (DL), can be effectively used for all descriptive and predictive operations, which are for the problems in reason–result (input–output) balance. ML/DL usage is critical because dynamically updated/changed Metaverse factors often need probabilistic and scalable (flexible) directives. In Metaverse setups, different ML/DL models can be used for different types of data. Their usage is important for also outcomes obtained regarding Digital Twins. ML/DL employment has a wide spectrum from Metaverse infrastructure to environmental dynamism and even bot decision-making. In the typical Metaverse setup, big data is essential for ML/DL, because the platform will include data with all characteristics (e.g., variety, velocity, volume, value) [27] of the big data. An effective way to employ Machine/Deep Learning for the Metaverse is also designing hybrid formations, which are dealing with multi-channel data and/or shaping the Metaverse data step by step.
- **Running recommendation systems**: Because recommendation systems are common in today's user-oriented platforms (e.g., social media, video streaming, e-trade), Metaverse highly requires using recommendation algorithms on the background. By using AI-based recommendation systems, objects and avatars of Metaverse can be provided with the smart matches for triggering socialization, buying, and many different tasks to do. Since Metaverse includes both characters (user avatars, bots) and dynamic objects, both collaborative filtering [28] and content filtering [29] of recommendation system methods will be applicable effectively.
- **Ensuring intelligent optimization**: Intelligent optimization of the AI field is effective for the mathematically modeled real-world problems under some objectives as well as constraints. By using intelligent optimization algorithms, it is possible for the Metaverse environment to find out optimum parameters for the actions and dynamic occurrences. Additionally, load balancing and role share for the technological components and ecosystems of the Metaverse can be modeled mathematically so that they are controlled through the way of optimization. In terms of intelligent optimization methods, continuous optimization [30] will be effective for solving numerical issues while combinatorial optimization [31] will be applicable to many NP-hard problems regarding complex interactions in the Metaverse environment. Because of the complexity in the Metaverse, majority of optimization problems should be multi-objective [32] in terms of modeling.

- **Using rule-based AI**: Except from probabilistic problems, Metaverse environments may come with also deterministic problems, which do not require advanced ML/DL usage. In this case, the related problems can be effectively solved with rule-based AI techniques since such use of AI corresponds to only determined rule and facts [33]. Use of such techniques is useful for the cases needing immediate action in the system flow. Also, distributed system infrastructure (e.g., blockchain) benefits from rule-based AI for extended security or creating advanced smart contracts.

2.3 Scenarios for Artificial Intelligence in the Metaverse

For a live Metaverse platform, use of AI can be understood better by thinking about scenarios. AI support for Digital Twins and the Metaverse framework has complicated connections among the employed technologies as well as objects. But by eliminating details, AI support can be explained by analyzing a Metaverse platform in terms of two parts: **infrastructure platform** and **action platform** (Fig. 3). Infrastructure platform uses AI for sustainability of the system and performing any required operations not visible to the user side. On the other hand, action platform is the actual environment where all the virtual lives are happening with smart touches by the AI. Existence of Digital Twins is in the related AI solution ways expressed before.

Employment of Digital Twins and the virtual life in the Metaverse has endless combination of scenarios for AI usage. But, for both present and future states of the Metaverse, some scenarios can be thought practically. That is the way to see how AI can be used in the Metaverse accordingly. Each scenario can be associated with ecosystem(s) (Fig. 1), one of the platforms (Fig. 3), and possible AI solutions (Fig. 2). Table 2 provides a wide list of AI usage scenarios in detail.

As it is shown in Table 2, AI has an intensive role on creating the desired interactivity and smart cycles within the Metaverse framework. Although the dynamic nature of the virtual life and synchronously happening events, present and future version Metaverse platforms employ complicated, mostly hybrid AI solutions. These are done by deriving outputs from ML/DL models and making these inputs for the next AI components like intelligent agents. In detail, chaotic nature of the Metaverse has the potential of uncontrollable wide Metaverse setups, but the most alarming issue is with the AI-oriented security issues. As AI systems are already under attack of

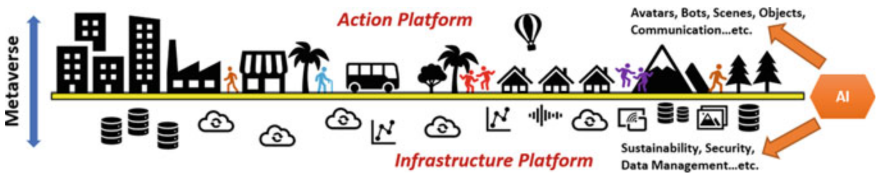

Fig. 3 Artificial Intelligence support for the two-part Metaverse

Table 2 Artificial Intelligence usage scenarios for the Metaverse platforms

Scenario	Ecosystem(s)	Platform	AI solution ways
*'Avatars receive recommendations for new contacts, tasks, works, trade…*etc.*'*	Sociality, avatar	Action	Recommendation systems, ML/DL models
'Avatars interact, socialize each other, meets somewhere, perform something together.'	Sociality, avatar	Action	Intelligent agents, ML/DL models, intelligent optimization
*'Avatars perform automated actions, adapt themselves to the bought objects, enrolled tasks, buildings…*etc.*'*	Avatar, content	Action	Intelligent agents, ML/DL models
*'Bots created by the system interact with the Avatars (users), other objects, scenes…*etc.*'*	Avatar, content	Action	Intelligent agents, ML/DL models
'The virtual world adapts physical objects to their digital twins and/or creates virtual assets to be interacted.'	Content	Action	ML/DL models, intelligent agents, intelligent optimization
'Data creation and balancing of the virtual content is managed by the system.'	Content	Infrastructure	ML/DL models, intelligent optimization, rule-based AI
'Legal/illegal actions are tracked and the necessary actions are taken in case of any problem.'	Legality, avatar, sociality	Infrastructure	Rule-based AI, ML/DL models
'Avatars buy, sell something, work/earn money, perform bank operations.'	Avatar, virtual economy, content, sociality	Action	Rule-based AI, intelligent optimization, ML/DL models
'The system processes money operations, control transactions, ensure decentralized data management.'	Security and trust	Infrastructure	Rule-based AI, intelligent optimization, ML/DL models

(continued)

Table 2 (continued)

Scenario	Ecosystem(s)	Platform	AI solution ways
*'The system is kept sustainable with new content creations, virtual life cycles in the environment, triggering interactions among avatars, objects…*etc.*'*	Content, avatar, sociality	Infrastructure	Intelligent agents, ML/DL models, intelligent optimization

malicious methods, AI use in Digital Twin technology and the resulting Metaverse environments should be discussed widely.

3 Artificial Intelligence-Oriented Security Issues

In Metaverse and Digital Twin technologies, cybersecurity is associated with availability, accessibility, integrity, and confidentiality [34]. Any problem in one or more of these factors may result break downs and loses of data, money, and prestige in terms of stakeholders. Specifically, AI components in Metaverse and Digital Twins are very sensitive in causing problems. Because availability and accessibility may be affected badly if AI software/hardware interfaces are unreachable, integrity may be missing if attacks cause errors in data or bias in AI decisions, and confidentiality may be lost when sensitive, critical data may be made open by AI models. In the Metaverse case, there are complex data processing aspects causing AI to be beyond the human control often. That is too important when the attacks for AI are taken into consideration. In recent years, there has been a great increase in malicious actions against AI-based systems. That is because smart tools take place at all parts of the daily life and the twenty-first century has been already dominated by the AI. Since AI is used in different platforms, hacking of such platforms may be done through AI medium. That is similar for the technologies of Metaverse and Digital Twin. As having a futuristic value, the Metaverse seems to be in the center of malicious intentions because it will host digital representations of people actions. Except from the security issues associated with other technological components of the Metaverse, the AI factor needs more elaborate evaluation to help building robust Metaverse of the future. From a general perspective, AI-oriented security issues may be examined under three titles as follows:

3.1 Attacks

Attacks to AI-based systems is a trendy malicious action in the context of AI security. In detail, any kind of AI technique is under risk but majority of attacks are related to ML/DL models. Attacking ML/DL models are done in order to manipulate their outputs. So, Metaverse objects, which are connected directly or indirectly with ML/DL effects, can be manipulated with the designed attacking methods. From a general perspective, attacks for ML/DL can be classified according to targets:

- **Attacks to the data**: This type of attack affects ML/DL models indirectly. Because ML/DL models are capable of learning the target problem from the data, any manipulated data can change the decisions of ML/DL. Such changes can allow malicious users to hack virtual life in the Metaverse environment. That is also critical for Digital Twins as attacks to the data can cause false predictions or manipulated directives for the employed ML/DL infrastructure. In the literature of AI safety, attacks to the data are examined under the topic of **adversarial attacks** [35–38]. In this context, manipulated (hacked) data are called as **adversarial example**. Considering the big data in Metaverse platforms, it is difficult to detect data attacks. But as a result of advancements in defensive AI methods, there are different types of solutions to detect and eliminate adversarial attacks [39–41]. Actually, the data-oriented attack causes the model to be attacked as manipulated input data affect the ML/DL model mechanisms. In other terms, if the attacker knows about details of the ML/DL model, the data attack can be designed with very high success rates.
- **Attacks to the model**: Except from attacks to the data, ML/DL models can be directly under attack. In this type of attack, the main purpose is to affect parameters of the ML/DL model so that the learning and inferencing mechanisms work false (or at least in the direction of malicious outputs). That can be possible with malicious parameters directly used by the ML/DL model. Actually, this is possible when the ML/DL model receives input for the parameters from the user side. However, that is not seen often in today's complex smart software systems. In the case of Metaverse, ML/DL models can use parameters, which are not open to the user side. However, manipulations over avatars, bots, virtual objects, and even methods for Metaverse tasks (e.g., coded functions for buying, playing, working actions) can be turned into data attacks or change the parameters for ML/DL training. A typical Metaverse may employ flexible model architecture where total number of layers, learning rates, etc. are determined according to the dynamic state in the Metaverse. Eventually, the changed parameters can break the proper working mechanisms of the ML/DL models. As a result of butterfly effect, the whole Metaverse environment can be affected by the unstoppable break downs in the AI infrastructure.

Considering data attacks and model attacks, the literature of AI safety classifies the whole attack techniques into two types: **white-box attacks**, which means that the attacker knows about parameters, architecture, and working mechanism of the target ML/DL model, and **black-box attacks**, which is for ML/DL model without any information about their details [38]. Some essential white-box attack techniques are known as Additive Adversarial Perturbations based on dL/dx, Fast Gradient Sign Method (FGSM), Basic Iterative Method (BIM), L-BFGS Attack, Carlini and Wagner Attack (C&W), and Adversarial Transformation Network (ATN) [42–46]. It is remarkable that especially ATN is a type of ML model, which produces adversarial examples. So that means a Metaverse may receive a virus, which is a variation of ATN to conquer the castle from the inside. Although black-box attacks seem having lower success rate, there is still chance to try some tricks like feeding ML/DL with some specific data to see the feedback and understanding the underlying mechanisms. In the literature, there is Heuristic Search for Boundary Attack and Substitute Attack, which uses the related tricks [47, 48]. For the Metaverse scenario, the highest priority is with black-box ML/DL models since there is a great complexity of smart interactions. So, it is certain that the black-box attack is the only model attack for the ML/DL infrastructure of Metaverse platforms. When the attacks are considering from the cybersecurity perspective, the ML/DL attacks are associated with the methods such as **poisoning**, **evasion**, **impersonation**, and **inversion** [49]. Of course, these methods include even hybrid data and model attacks with considerations white-box and black-box approaches.

3.2 Vulnerabilities and Bugs

Vulnerabilities and bugs are typical security issues for software systems. So, these issues are visible in even the most advanced AI-based software systems. Specifically, vulnerabilities may be seen because of hardware architectures, software codes with logical/technical drawbacks, and even mistakes by users. On the other hand, bugs are seen in software codes. Although detection applications can be applied over software systems to have information about level of vulnerabilities/bugs, the scenario is not same for AI infrastructure.

Vulnerabilities in AI in the Metaverse can appear as a result of wrong data or attacks. Because especially ML/DL models are evolving in terms of learning, vulnerabilities may appear in longer time period and as beyond of human control/sight. However, bugs may be detected easier if proper human-side tracking can be applied over AI infrastructure of Metaverse platforms. For Digital Twins in Metaverse platforms, vulnerabilities and bugs may be reason for wrong AI-based analyses in the digital copies. Such wrong AI-caused analyses may affect physical components badly.

For possible AI vulnerabilities inside the Metaverse, attacks by developed malicious AI attacks are too critical, because such attacks designed by AI may be difficult to be detected and the power of AI can be used for even creating vulnerabilities or specific bugs, which will simplify attacking processes. Complex data communication in Metaverse may hide AI attacks, and at the end, AI-based components such as bots, smart objects, scenes may start to act as mediums for common data communication security issues like spoofing, replay attack, or man-in-the-middle.

3.3 User-Based Issues

In terms of cybersecurity, the weakest factor is human. For even the strongest cyber system with all advanced defensive technologies and precautions, a simple human mistake may be cause for the breakdown of the system. Because the Metaverse is a technology built for the human activity in a virtual life, it is certain to see user-based security issues.

Thinking about the AI inside a Metaverse, intentional or unintentional actions by avatars (users) may confuse the AI resulting to easier attacks and vulnerabilities. Especially, intentional actions by avatars may be for manipulating the Metaverse objects, bots to gain advantages in the virtual life. However, such actions may cause problems in terms of AI security. As a result of interactions between avatars and smart components like bots, interactive objects/scenes, AI models of the Metaverse platform may start to create adversarial examples mistakenly, that may be because of unexpected avatar actions trying to trick the environment. So, whether their actions are intentional or unintentional, users can easily start negative butterfly effects on the whole Metaverse AI pipelines. User-based issues affecting the Metaverse AI is actually a problem of awareness and the literacy (of data, informatics, AI, and even Metaverse) (Fig. 4).

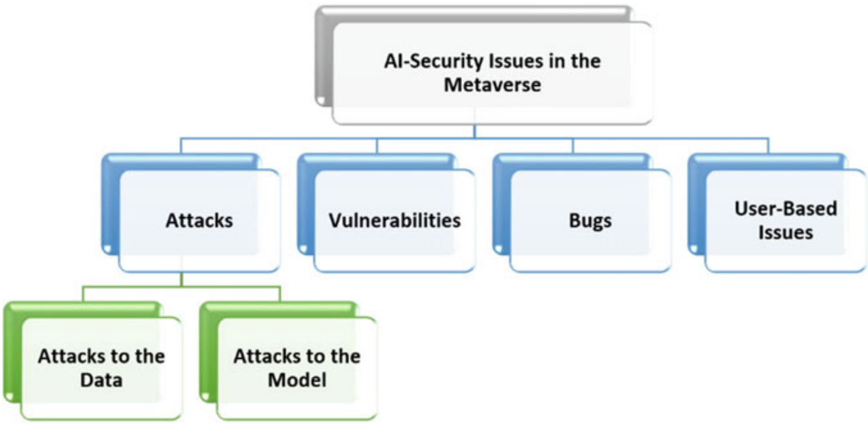

Fig. 4 General overview of Artificial Intelligence-oriented security issues in the Metaverse

4 Solution Recommendations

As it can be seen, there is a variety of AI security issues with the safety risks in the context of Metaverse technology. Because the Digital Twin technology seems to be essential for present and future versions of the Metaverse, the risk surface is even bigger. However, there is still chance to apply some solutions to deal with AI-caused security issues. As a result of evolving Metaverse, different measures may be required to derive more advanced solutions in the future, but now it is possible to think about some general solutions ways. In terms of solutions, it is possible to think about technical and societal aspects. Because the human factor is in the center of the Metaverse, analyses regarding human-based functions and auditing of the Metaverse technology (and the associated components) are important [50, 51]. By including the Digital Twin aspect, some solution suggestions are expressed in Table 3. In the table, different security issues are matched with solutions, explanations, and the associated solution aspect.

Table 3 shows a general guidance for possible actions to deal with AI-caused security issues. Security issues may be changed in time as a result of rapidly changing AI field and the applied techniques/models. But especially, human control over the technological tools is essential to draw the safe future of the Metaverse, with a sustainable virtual life inside it. Moreover, awareness and the technological literacy are too essential for the future societies.

5 Conclusion

This chapter provided a general overview about use of Artificial Intelligence (AI) in the context of Digital Twin supporting Metaverse. The first consideration was given to understanding how AI is applied for both Digital Twins and Metaverse platforms. After that, security issues regarding AI use and some solution suggestions were discussed accordingly. As the future of people socialization, working, trading, and entertaining are highly associated with the Metaverse technology; using AI-based systems and taking care of security issues for such systems are important topics to be analyzed elaborately. The concept of Digital Twin can be evaluated in a separate framework, but since Digital Twins are essential elements of the Metaverse, the discussion was expanded by considering a collaboration between Metaverse and Digital Twin.

As it is seen from the reached points, complexity of Metaverse needs use of advanced AI technology. However, use of AI brings security risks, which should be managed in the context of AI domain. As long as even the most recent smart technologies can be examined from the same view of AI security, Metaverse has more critical value as it will shape the future life of the society. Attacks performed through data and the AI models have the highest priority while vulnerabilities, bugs, and user-side problems are also rising as AI becomes a blurred technology for the

Table 3 Some solution suggestions for the security issues of Artificial Intelligence in the Metaverse

AI-based security issue	Solution	Solution aspect
Data attacks and model attacks	**Using defensive techniques**: There are many defensive techniques against the attacks. These can be applied successfully for Digital Twins and the Metaverse	Technical
Data attacks	**Creating smart, synthetic data against data with issues**: It is possible to create synthetic data in order to ensure balance in the data with bias, malicious content	Technical
Model attacks	**Developing robust ML/DL models**: Detailed design and development of robust ML/DL models will be effective to deal with possible security issues	Technical
Model attacks	**Developing safe bots within safety forces**: Metaverse platforms can be supported with AI safety forces including safe bots, which are tracking all avatar actions, dynamic changes within Digital Twins and the Metaverse platform	Technical
Data attacks and model attacks	**Training experts on secure AI development**: Effective training programs can be realized to have expert people, who have high awareness for AI safety in the Metaverse	Societal
Vulnerabilities and bugs	**Developing additional components to eliminate vulnerabilities as well as bugs**: Different types of modular components against AI vulnerabilities and bugs can be built. Since these components are modular, they can be integrated to current AI infrastructure in the Metaverse	Technical
Vulnerabilities and bugs	**Applying detailed tests for vulnerabilities and bugs**: Tests for detecting vulnerabilities/bugs can be done to prevent from possible risks/issues	Technical
User-based issues	**Training people with awareness of vulnerabilities**: Training programs to educate people for possible AI-caused vulnerabilities will be an effective solution for robust Digital Twins and Metaverse with AI support	Societal
Data attacks	**Data scientists with high awareness of safe data analytics**: Data scientists having strong knowledge and abilities on safe data analytics can be grown up for having safe data support for the AI of Metaverse platforms	Societal

(continued)

Table 3 (continued)

AI-based security issue	Solution	Solution aspect
All issues	**Establishing world-wide regulations, control mechanisms, and councils**: Advanced technologies such as AI, Digital Twin, and Metaverse require worldwide management mechanisms. Such solution will be highly effective for all possible AI-based security issues in terms of the Metaverse technology	Societal

humanity [52, 53]. Considering solutions against malicious intentions toward the AI, scientific and technical research has many defensive methods. Except from that, awareness in using Metaverse platforms, preparing the necessary worldwide regulations, establishing control mechanisms and councils take remarkable role when the societal side of the Metaverse is thought. By considering possible scenarios, different counter actions can be taken and sample guidance's can be designed to deal with the AI-caused issues. The remaining security actions except from AI factor are connected with the field of cybersecurity.

This chapter provided a general, recent overview to understand the AI in terms of Metaverse platforms. Research for the Metaverse and the included Digital Twin factor still needs more steps to go. So, detailed analyses from both natural and social sciences should be gaining momentum immediately. The technological flow in the twenty-first century requires interdisciplinary sight, that may be a good starting point to move. In addition to the contributions by the Computer Science and Engineering, societal, lawful, educational, and even psychological aspects may be blended in common discussion for creating better awareness on not only Metaverse but also employment of AI in it.

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