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Cognitive digital twin:
An approach to improve the maintenance management

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Cognitive digital twin: An approach to improve the maintenance management

Digital technology is progressing at a rapid pace. Our need as an international defence company, whose business is underpinned by a deep understanding of technology integration and engineering, is to understand its impact and benefits.

Working in collaboration with Cranfield University we're pleased to present this new research into Digital Twins, looking at the role this technology can play in asset maintenance.

For businesses like ours, Digital Twins can provide a means to better understand real-world entities. We utilise a Digital Twin approach across Babcock to better understand asset performance and enable prediction of future use to allow us to prevent failures, better plan maintenance and optimise our resources, inventory and supply chain to increase asset availability and reduce through-life costs.

The use of ontologies as part of a structured, repeatable approach to the definition, creation and management of digital twins is key to helping us realise their full potential in the engineering lifecycle. This allows us to manage the complexity of an individual twin and the interoperability of multiple twins as part of a system of systems that can be scaled to model real-world behaviours of assets and the environments in which they operate.

This research also examines the complex integration of different types of technical and contextual data a digital twin can provide. It incorporates technologies and techniques such as Artificial Intelligence and machine learning, data analytics and multi-physical simulations to model and predict behaviour – providing vital information to asset owners.

This paper importantly explores the impact of asset degradation and shows how collecting data across the life cycle of assets, together with accurate degradation models, can help us better predict the remaining useful life of components. In this way, we can move from reactive maintenance to proactive maintenance, avoiding downtime and optimising maintenance planning and costs through predictive maintenance.

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Review

Cognitive digital twin: An approach to improve the maintenance management

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ABSTRACT

Digital twin (DT) technology allows the user to monitor the asset, specifically over the operation and service phase of the life cycle, which is the longest-lasting phase for complex engineering assets. This paper aims to present a thematic review of DTs in terms of the technology used, applications, and limitations specifically in the context of maintenance. This review includes a systematic literature review of 59 articles on semantic digital twins in the maintenance context. Key performance indicators and explanations of the main concepts constituting the DT have been presented. This article contains a description of the evolution of DTs together with their characterisation for maintenance purposes. It provides an ontological approach to develop DT and improve the maintenance management leading to the creation of a structured DT or a Cognitive Twin (CT). Moreover, it points out that using a top-level ontology approach should be the starting point for the creation of CT. Enabling the creation of the digital framework that will break down silos, ensuring a perfect integration in a network of twins' scenario.

Contents

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Introduction

The digital twin (DT) definition has evolved in the last decade and still changes depending on applications and purposes. Generally, we can briefly define a DT as a dynamic digital representation of a real entity, it gains value if applied across the whole life cycle of the asset of interest.

DT cooperates well with other related paradigms, such as the cyber-physical systems and industry 4.0, and it is predicted that half of the large industrial companies will implement DT technology by 2021, resulting in those organisations gaining a 10% improvement in effectiveness [1]. The National Infrastructure Commission (NIC) in 2017 states that "*the UK needs a digital framework for data on infrastructure to harness the benefits from sharing better quality information about its infrastructure; how it is used, maintained and planned. A digital framework will enable a better understanding of interdependencies between infrastructure sectors and help to break down silos.*" [2].

Degradation is a continuous process pertaining to the deterioration of the structure of the asset. Complex engineering assets are characterised by the fact that their maintenance phase is the longest-lasting and resource-consuming phase of the life cycle and more efficient maintenance management could lead to efficient use of resources and optimisation of costs [3]. Degradation in complex engineering assets is a demanding and challenging area and understanding & establishing a cause-effect model will help maintain the asset. Such damage reduces performance and shortens the life of the product. Collecting data across the life cycle together with accurate degradation models, lead the DT to better predict the remaining useful life (RUL) of components. In this way, we can move from reactive maintenance to proactive maintenance, avoiding downtime and optimising maintenance planning and costs (predictive maintenance).

A DT stores information about its physical counterpart throughout the life cycle and can use those pieces of information to perform predictive analytics reducing unscheduled downtimes. It also helps in making more accurate decisions based on reliable information. Most organisations are siloed internally resulting in an expensive lack of collaboration between those siloed departments. Managing assets with data and specifically with DTs can reduce business risks and improve collaboration [4]. Today, early in a system's acquisition, stakeholders invest in models that aid in communication across the whole supply chain [5].

Successful use of DTs faces significant data management challenges and needs well-organised guidance [6]. Another challenge in deploying DTs is that there are limited standards for implementing them [5], and different companies may use different definitions and relations within their data architectures, increasing the incompatibility of systems. A new framework for connected DTs should be developed and it should be based on an ontological approach. Ontology is a branch of philosophy that studies the kind of things that exist and the relation between them. With this framework, DTs get closer to each other as this facilitates the effective integration of the models, data, and systems. The authors of this paper pursue the employment of a top-level ontology based DT to address the above-mentioned interconnectivity issue. In fact, DTs based on the same domainless upper ontology facilitate the integration of twins, enabling the creation of a form of a network of twins. The latest executive report from Accenture produced in March 2021 highlighted that 87% of the executives acknowledge DT technology as an increasingly fundamental tool to enable a strategic collaboration with business partners [7].

Interest in DTs is growing fast across industry and academia. As seen in Fig. 1, the total amount of publications in 2021, is about half of the total amount of publications published over the last 7 years. Therefore, all literature reviews published in 2020 did not take account of the majority of publications released so far.

There are already several reviews about DTs across the whole life cycle that also depict their main characteristics. Instead, this review focuses on analysing the maintenance and health monitoring phase of the life cycle, as one of the more complicated phases for complex engineering assets [5]. For this reason, this paper aims to present a review of DTs in terms of technologies used, applications, and

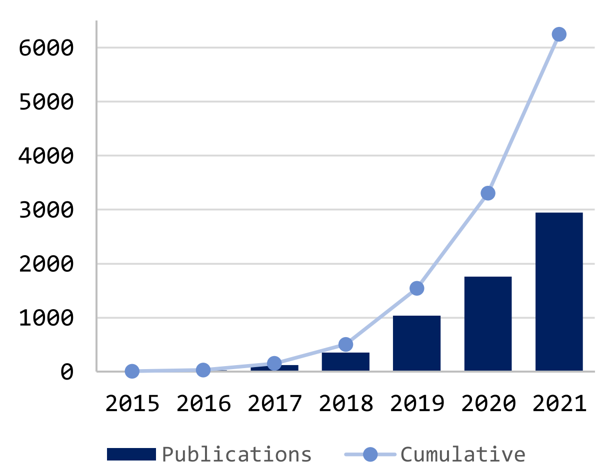

Fig. 1. Number of publications containing "digital twin" in title/abstract//keywords on the Scopus database from 2015 to 2021.

limitations, specifically for the maintenance phase of the asset's life cycle. Moreover, this paper aims to introduce the association between the concepts of DT and ontology to improve the interoperability of DTs. Previous research reported by D'Amico et al. provides an initial approach linking the use of an ontology to develop a DT [8]. This association of ontology-based DT has led to the recent introduction of the concept of cognitive twin (CT) or cognitive DT. Lu et al. define the CT as a DT *with augmented semantic capabilities for identifying the dynamics of virtual model evolution, promoting the understanding of interrelationships between virtual models and enhancing the decision-making based on DT* [9]. One of the aims of this paper is also to guide the reader from the evolution and review of the standard concept of DT used in maintenance to the opportunity of implementing the CT to improve maintenance management.

A Systematic Literature Review (SLR) has been carried out to address the above-mentioned aim. Systematic approaches to the literature hold the potential to demonstrate greater clarity, to possess more validity, and to manifest improved auditability [10]. Booth et al. composed a comprehensive methodology to conduct an SLR [10] using a 4-stage analytical framework: Search, AppraisaL, Synthesis and Analysis (SALSA). This generic approach is well validated and can be specifically applied across different fields [11,12]. Therefore, it has been adopted in this review to provide a clear and valid analysis of the literature published in the field of DTs for maintenance & health monitoring, identifying relevant research gaps.

The rest of this paper is organised into four sections. Following this, the literature review section reports complimentary review papers about DTs. The methodology section reports the procedure that has been carried out in this paper. The results section reports the results and the characterisation of the DT for maintenance, highlighting the concept of DT, its evolution over time, and the difference with existing models like BIM (Building Information Modelling). Finally, the conclusion section reports findings, limitations, and proposes future research steps.

Literature review

Several literature reviews about DTs have been published so far. Searching on the Scopus database for ("digital twin" AND "review"), 436 papers have been published from 2015 to 2021. Fig. 2 shows the distribution of the literature review publications about DTs. Specifically, at the time of this review (2020), searching for ("digital twin" AND "systematic" AND "literature review"), 15 papers have been published between 2019 and 2020, and just 4 of them are journal articles.

Since this article would be a systematic review, a brief analysis of the above-mentioned 4 systematic review journal articles has been carried out.

After a systematic literature review, Bányai et al. [13] in their work introduced the production structure as a cyber-physical system focusing on logistics. In that research, DTs are solutions to support prediction and optimisation performance. The search string used there was ("manufacturing" AND "logistics" AND "optimization") and the database used was Web of Science. Bányai et al.*'s* [13] study considered DTs only as part of their production system and exploited associated digital technologies to optimise both the manufacturing as well as the logistics associated with it.

Wanasinghe et al. [14] focused the systematic review on the application of DTs in the oil and gas (O&G) sector. The authors of that review considered Journals, books and conference papers published between 2003 and 2020 in Elsevier, IEEE Xplore, OnePedro, Scopus, and Springer databases. The search string used in that review was ("digital twin" OR "digital twins" OR "digital models" OR "digital environment" OR "digital environments" OR "virtual twin" OR "virtual twins" OR "virtual environment" OR "virtual environments") AND ("oil" AND "gas"). In their review, Wanasinghe et al. were looking at what is a DT, the status of DT deployment in the O&G industry, and finally key opportunities and key challenges in DT deployment in the O&G industry. They highlighted the top ten enabling technologies for DTs as well as the top ten O&G related application areas. In the latter classification, asset integrity monitoring has been highlighted as the top DT application. The review also pointed out that existing data integration is one of the major challenges in today's implementation of DT, particularly in the O&G industries.

SALSA framework	
Step	**Description**
SEARCH	Find the scope (PICOC framework)
	Preliminary literature search
	Full literature search and reference management
	Selection of articles
APPRAISAL	Quality assessment and selective data extraction
SYNTHESIS	Data synthesis
ANALYSIS	Data analysis
	Reporting

Fig. 2. Distribution of literature review publications about DTs (Tool: sankeymatic.com).

Götz et al. [15] performed a systematic literature review to map use cases of DT, Internet of Things (IoT), blockchain and smart contract technologies. The review aimed to investigate the feasibility of a blockchain-based DT for asset life cycle management. Particularly looking for functionalities, interoperability with current applications and integrability enablers for blockchain-based DT. Götz et al. [15] looked at Scopus and Science Direct databases and limited their search to publications between 2019 and 2020 with the following search strings: ("digital twin" OR "Internet of Things" OR "Blockchain" OR "smart contract") AND ("asset" OR "facility" OR "building" OR "real estate" OR "life cycle" OR "management"). The authors in the conclusions highlighted the significant potential of the DT technology application, specifically focusing on the real estate industry. They also pointed out the importance of creating a common ontology ecosystem to better implement the blockchain-based DT for pilot testing.

Jones et al. [16] provided a systematic literature review and a characterisation of the DT, in addition to identifying gaps and required areas of future research. The research was performed at the end of 2018, the search string was ("digital twin") in the Google Scholar database. They also added all the papers that cited the three seminal papers of DTs written by Grieves [17,18] and Tao et al. [19], resulting in a total of 92 publications. The authors identified 13 characteristics of the DT and gaps in research that include DT across the product life cycle. Particularly, Jones et al. pointed out that the DT would benefit from a more detailed comparison and review, mentioning health monitoring and prognostics as an example.

Results obtained in the above-mentioned published articles strengthen our motivation to publish this systematic literature

SALSA framework	
Step	Description
SEARCH	Find the scope (PICOC framework)
	Preliminary literature search
	Full literature search and reference management
	Selection of articles
APPRAISAL	Quality assessment and selective data extraction
SYNTHESIS	Data synthesis
ANALYSIS	Data analysis
	Reporting

Fig. 3. SALSA methodology steps description.

review. As mentioned before, the scope of this paper is to investigate applications of DTs that focus on the maintenance and health monitoring phase and not on the whole life cycle.

Methodology

The literature review is defined in [10] as "*a systematic explicit, and reproducible method for identifying, evaluating, and synthesising the existing body of completed and recorded work made by researchers, scholars, and practitioners*". Therefore, to make the literature systematic, the methodology applied in this article follows the frameworks given in the book "*systematic approaches to a successful literature review*" by Booth et al. [10]. The analytical framework proposed by Booth et al. is well validated and consists of 4 steps: search, appraisal, synthesis, and analysis (SALSA framework). Fig. 3 presents a description of the methodology's steps. The four steps are described in the following subsections.

Step 1 – Search

Defining the research scope is necessary to mould clear, answerable questions. This review adopted the PICOC (Population, Intervention, Comparison, Outcome, Context) framework (Table 1) to frame the aim, objectives, and research questions.

Aim, objectives, and research questions

Through the PICOC framework (Table 1), the aim has been derived, considering also the motivation highlighted in previous sections. Therefore, this review *aims* to investigate the possible standards, principles, and methodologies in using DTs for the maintenance of complex engineering assets, as well as to characterise a DT model that can best suit this application.

Actions taken to achieve the aim are the following *objectives*:

a) Identify current practices in using through-life DTs to track the health status of assets.
b) Investigate DTs that can predict the remaining useful life of an asset.
c) Perform a thematic analysis to understand key aspects of a DT for maintenance management.
d) Characterise a DT model for maintenance planning.

The research questions that this paper aim to answer are the following:

a) How DTs for the maintenance phase of the life cycle are developed?
b) How can a DT be characterised for maintenance?

Search strategy for identification of articles.

A defined literature search strategy is required for this review to be systematic. These will then be filtered according to the inclusion and exclusion criteria which define the filters that have been considered for the selection of the studies for this review (see Table 2). For this review, search databases, search string, and article types have been also identified.

Initially, the methodology of this paper focused more only on DTs and maintenance related concepts. After reviewers' feedback, the search strategy has been refined. Fig. 4 shows a set diagram representation of how the authors move from the previous strategy to the new search strategy. The new search string has been refined including the *semantic* set as the intersection with the *DT* and *Maintenance* set. This is to make the literature more comprehensive and aligned to the authors' research area. Moreover, the number of databases has increased from 1 to 3 and conference papers have been also included.

After a preliminary literature search, described in the previous section, the authors became aware of synonyms used in research for DTs and research gaps highlighted in other reviews. Eventually, the search string that has been chosen for this review must contain the word "digital twin" and its synonyms along with maintenance related words and semantic/ontology words. Cyber-physical production systems (CPPS) have been considered a synonym for DTs. CPPS publications were suggested by the reviewers and together with the semantic approach have been found aligned with the purpose of this review. Later in the methodology, the authors will refer just to DTs, considering both DTs and CPPS, because DTs havebeen chosen as the main focus of the research project. The search string adopted can be seen in Table 3. The search string is applied for searching in title, abstract, and keywords among the papers in three scientific databases, Scopus, IEEE eXplore, and Web of Science.

Mendeley (https://mendeley.com) has been used as a tool to manage all the references, due to its strong community and support, as well as the integrated pdf viewer and the add-in for Microsoft Word used to write this review. All the available pdf files have been downloaded and uploaded to Mendeley.

Table 1
Research scope definition - PICOC framework.

Concept	Description
Population	DTs and CPPS use semantic capabilities that are used to track through-life degradation in the maintenance phase.
Intervention	Investigation of existing techniques – DTs for health monitoring, maintenance, and asset management purposes.
Comparison	Current industrial practices – How does the new proposal compare to the existing methodology?
Outcomes	Characterisation of an open framework of DT, with flexible and reliable interfaces that enable interconnections between different agents.
Context	Maintenance engineering.

Table 2
Inclusion and Exclusion criteria.

Inclusion criteria (IC)	1) Publications related to health and degradation assessment
	2) Publications related to maintenance
	3) Publications related to asset management
Exclusion criteria (EC)	1) Not met inclusion criteria
	2) Not written in English
	3) Full paper not available
	4) Published before 2011

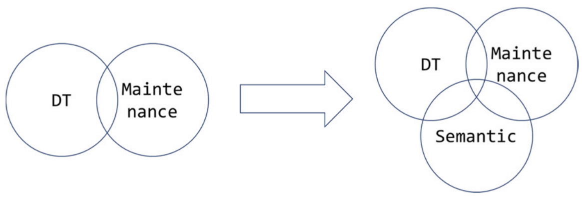

Fig. 4. From the previous to the new search strategy.

Step 2 – Appraisal

The appraisal phase consists of the evaluation of search results to refine the number of publications to those relevant and in accordance with the scope of this review. In order to make this process systematic, a set of specific inclusion and exclusion criteria have been used based on the PICOC framework (Table 1). Table 2 list the inclusion and exclusion criteria adopted within this systematic review.

The literature search ran on the 06th of April 2022. The search resulted in 59 publications in total. Subsequently, 7 papers were not available for download. The authors classified those 7 papers as not relevant according to the abstract and also due to the low number of citations. However, the authors took them into consideration for the initial part of the synthesis (Publication elements in Table 4). The publications, hence, have been analysed, extracting and classifying all the relevant information, as described in the following step.

Step 3 – Synthesis

The synthesis phase consisted of the extraction and classification of relevant information from the selected articles. This step of the review will identify what the literature says, in the next step, instead, the analysis, what the literature means. The data extraction phase consisted of filling a Microsoft Excel spreadsheet with data from articles, to manage and allow different studies to be appraised consistently, as suggested in [10]. This included records that can be summarised in four main categories: publication elements, study elements, characteristics, and conclusion elements. Publication elements were recorded for the 59 sources found. All the records selected for the synthesis phase are listed in Table 4. The eligibility was established in three main stages: (i) title - abstract - keywords screening; (ii) introduction - conclusions reading; (iii) and full-text reading. This allowed papers to be summarised into thematic categories identifying relationships for synthesis.

Table 4
Records for the synthesis analysis.

Publication elements	DOI
	Title
	Authors
	Journal/Conference
	Name
	Year
	Keywords
	Inclusion Criteria
Study elements	Field/Sector
	Purpose of the paper
	Research question(s)
Characteristics	Definition of DT
	DT or CPPS
	Life cycle stage(s)
	Ontology information
	Reasoning engine
	Taxonomy
	Knowledge graph info
	Data exchange protocols for DT
	Data mapping dictionary / Format
	Middleware platforms for SW development
	Databases and data management
	Data format, data model, and representation
	Modelling and simulation software
	Virtualisation microservices
	Integration in existing standards
	Interface
	Visualisation
	Cloud
	Edge computing
	Rate
Conclusion elements	Benefits
	Findings
	Limitations
	Future works

While the subdivisions of *Publication elements*, *Study elements*, and *Conclusion elements* categories are typical of almost every SLR, the *Characteristics* subdivision identifies attributes related only to DTs. Taking advantage of other reviews and characterisations already published, a comprehensive subdivision that best represents the typical characterisation of a DT has been implemented. An example of a technical and comprehensive review of techniques used to create DTs was published by Lim *et. al.* in 2019 [20]. That review contains specific technical aspects that everyone who wants to develop a DT needs to deal with. Other broader characterisations linked with the DTs' world can be also found in other systematic reviews, such as the ones mentioned in the literature review section of this article.

Fig. 5 shows the results of the thematic analysis dedicated to the creation of DTs. This helps the understanding of the specific characteristic's category from Table 4.

Step 4 – Analysis

The analysis phase consisted of the extraction of data from the reviewed articles into the categories previously introduced in the previous section (Step 2 - Appraisal). This phase is comprised of three steps [10]: (i) thematic analysis, which covers each theme and

Table 3
Screening criteria.

Database	Scopus, IEEE eXplore, and Web of Science
Search string	("digital twin" OR "digital thread" OR "virtual twin" OR "cyber twin" OR "digital replica" OR "cognitive twin" OR "cognitive digital twin" OR "digital data hub" OR "cyber physical production system" OR "CPPS" OR "digital shadow" OR "digital mirror") AND ("degradation" OR "deterioration" OR "maintenance" OR "failure" OR "damage" OR "defect" OR "downtime" OR "maintenance repair and operation" OR "MRO" OR "health management" OR "condition monitoring" OR "CBM" OR "condition based monitoring" OR "remaining useful life" OR "RUL") AND ("ontology" OR "semantic")
Document type	Journal and conference paper

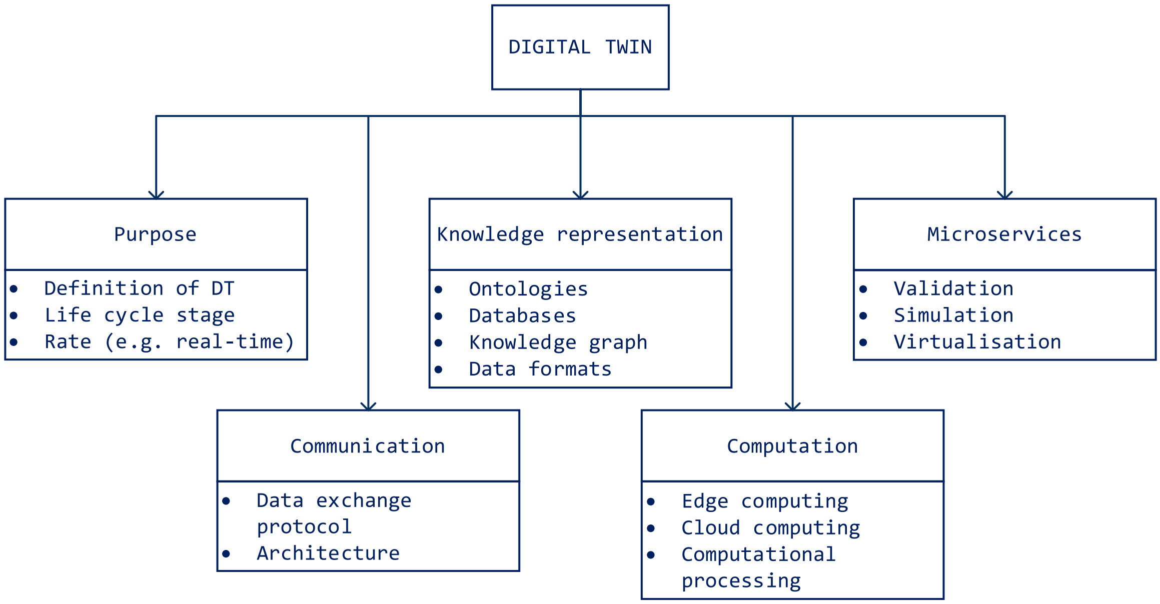

Fig. 5. Classification of the category's division for the review of DTs.

correlations over the reviewed articles, assessing either qualitative data or quantitative results. This step is described in this section; (ii) discussion of results, which evaluates the outcomes to answer the research questions of this review (see 3.1.1) and will be discussed in the results section; (iii) conclusions are drawn, which include findings, limitations of the study and future research opportunities, discussed in the conclusion section.

The following sub-section will describe the 4 characteristics found in the previous sub-section: publication elements, study elements, characteristics, and conclusion elements.

Publication elements

This part of the analysis includes general basic elements about the 59 publications found before the full-text reading:

a) DOI (Digital Object Identifier)
b) Title of the publication
c) Authors
d) Journal or conference name
e) Year of publication
f) Keywords
g) Inclusion criteria

The points (a to e) are standard data, and the last one (g) inclusion criteria, is a record added to understand what inclusion criteria the examined article has met.

Study elements

In this part of the analysis, further elements of the articles were collected, such as:

a) Field/Sector
b) Purpose of the paper
c) Research question(s)
d) In this phase, there was further contextualisation about the purpose that each reviewed article dealt with, for instance, the type of sector and industry the DT that was applied. The purpose or the solution which led to the deployment of DT. Besides, the fundamental research questions in the publications have been identified.

Characteristics

This was the core part of the analysis, where specific characteristics of each DT were gathered. As can be seen in Fig. 5, each record is classified within a subcategory. The subcategories are:

a) Purpose
b) Communication
c) Knowledge representation
d) Computation
e) Microservices

The following is a brief description of what is included in each subcategory.

Purpose

Since there is limited standardisation about DTs, today everyone shapes the definition of DT according to the purpose they want to use this technology. Therefore, in the purpose subcategory specific definitions of the DT applied to each case have been categorised, the pace, or rather the rate of data collection (if real-time or other), and the life cycle stage in which the DT is applied. All the selected articles handle DTs for maintenance, specifically, looking at the O&S phase of the life cycle. But in this analysis, we wanted to check if any DT considered for that specific purpose, was also designed to assist the asset through the whole life cycle (from the concept stage to the retirement & disposal stage). Particularly, considering feedback from the service stage to the design stage.

Communication

The communication subcategory includes information about how a DT performs the acquisition and transmission of data. The focus will be on the DT architecture, the structure that allows the DT to receive and transmit data. Data exchange protocols and middleware platforms to ease information exchange are also considered in this analysis. The specific characterisation of the technologies used in this part of the DT will be discussed in the results section.

Knowledge representation

The knowledge representation subcategory includes information about how the knowledge of the DT is represented. How the semantic of the DT is represented. In case there is an ontology if it is dedicated or referring to other top-level ontologies. Details about the reasoning engine running over the ontology have been considered. Knowledge graphs, the tools used, and the query language have been reviewed. The data format, data representation tools, and relational/non-relational databases have been evaluated.

Computation

The computation subcategory includes information about storage allocation, computational models for data processing, and machine learning methodologies employed in the specific application of the DT, including statistical optimisation approaches for data analysis.

Microservices

The microservices subcategory includes virtualisation tools that allow the monitoring of the physical process. Furthermore, the tools that allow the simulation to improve the decision-making process, and validation tools that enable the task verification to confirm accuracy and integrity.

Conclusion elements

This subsection includes the fourth and last category analysed for this review (see Table 4). This is to collect and list the outcomes of the reviewed articles, including the benefits of using DTs, findings, limitations, and future works suggestions.

Results

In this section, results for each of the four subcategories (publication elements, study elements, characteristics, and conclusion elements) are presented and discussed. Moreover, the characterisation of a DT for maintenance has been proposed below.

Publication elements

Fig. 6 shows the distribution of the selected 59 publications according to the publication year. As can be seen, just in 2021 have been published the same number of papers published from 2017 to 2020 (28 papers published in 2021 and 28 papers from 2017 to 2020). This trend clearly shows the increased growth in this area of research. The year 2021 by far has seen the largest number of publications in the area of DTs with semantic capabilities for maintenance, highlighting the importance and timeliness of this article.

Fig. 8 shows the distribution of the reviewed publications between Journal and conference papers. Conference papers are 34 out of 59 (58%), while Journal articles are 25 out of 59 (42%). The Sankey diagram in Fig. 7 shows the distribution of the 59 papers per year and per type of publication.

Table 5 and Table 6 show respectively the list of journals and conferences where the reviewed papers have been published. All the 59 selected articles are divided into these 2 tables.

Authors of the selected articles have been gathered and ranked. Fig. 9. shows just the list of authors that published two or more articles in this field (not only as of the first author). From this analysis, Ansari F., Kiritsis D., and Erkoyuncu J. are the top 3 authors in this specific field.

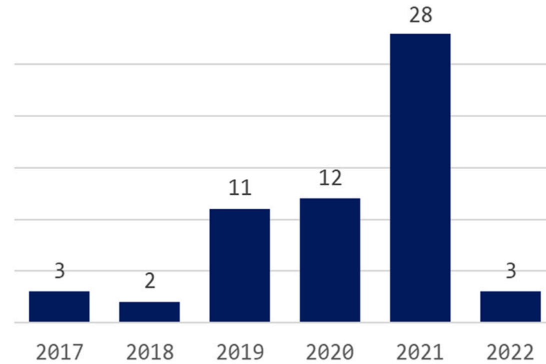

Fig. 6. Distribution of the reviewed publications per year.

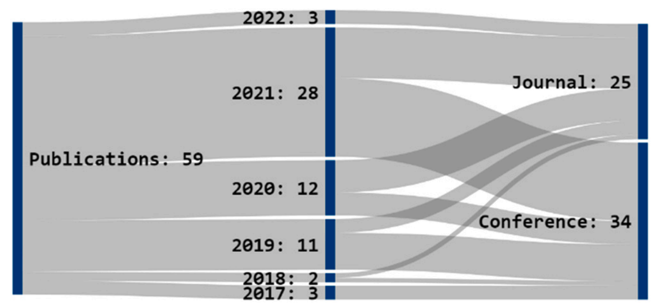

Fig. 7. Sankey diagram with the distribution of published papers divided per year and type of publication.

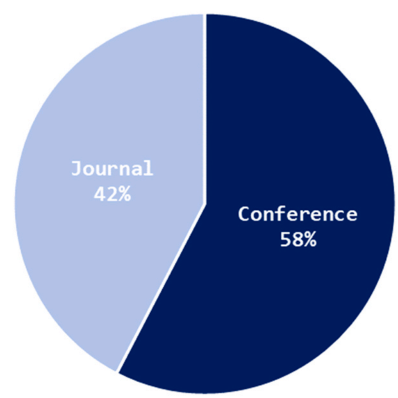

Fig. 8. Distribution of the reviewed publications between journals and conferences.

Fig. 12 shows the list of keywords used at least 3 times in the reviewed articles. Digital twins and synonyms have been used 31 times as keywords. The extended version and the acronym have been grouped (i.e., Asset Administration Shell and AAS).

Fig. 10 shows the distribution of the reviewed articles per IC (see Table 2). The pie chart shows that 50 (81%) papers are aligned with IC3 (asset management), whereas 8 papers (13%) are aligned with IC1 (maintenance). The remainder 6% (4 papers) are aligned with IC2 (health and degradation assessment).

Study elements

Fig. 11 shows the distribution of 59 publications per field of application. Following the description of each field of application adopted for this review.

- *Manufacturing* concerns semantic DTs used for health monitoring, maintenance, or asset management in manufacturing processes,

Table 5
List of the Journals.

Journal name	Ref.
Annual Reviews in Control	[21]
Applied Sciences	[22–24]
CIRP Annals - Manufacturing Technology	[25]
CIRP Journal of Manufacturing Science and Technology	[26,27]
Energy and Buildings	[28]
GENES	[29]
IEEE Access	[30]
IEEE Systems Journal	[31]
International Journal of Automation Technology	[32]
International Journal of Computer Integrated Manufacturing	[33]
International Journal of Production Research	[34]
Journal of Ambient Intelligence and Humanized Computing	[35]
Journal of Construction Engineering and Management	[36]
Journal of Nondestructive Evaluation	[37]
Knowledge-Based Systems	[38]
Magazine of Civil Engineering	[39]
Naval Engineers Journal	[40]
PFG-Journal of Photogrammetry Remote Sensing and Geoinformation Science	[41]
Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences	[42]
Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture	[43]
Sensors	[44]
Tunnelling and Underground Space Technology	[45]

such as CNC machine tools, automotive, gearbox, etc. This includes also publications about smart manufacturing, CPPS, robotics, and industry 4.0.

- The *civil* category focus is on the monitoring of structures mostly bridges, tunnels, and buildings.
- *Generic* is a category where DTs were studied with a domainless approach.
- *Infrastructures* refer to electrical systems components in power plants or buildings (e.g. batteries or fuel cells), or systems like renewable energy systems.
- *Transports* refer to DTs designed to monitor mobility systems, not only the car or the train but also the integration of intelligent vehicles in a smart city environment.

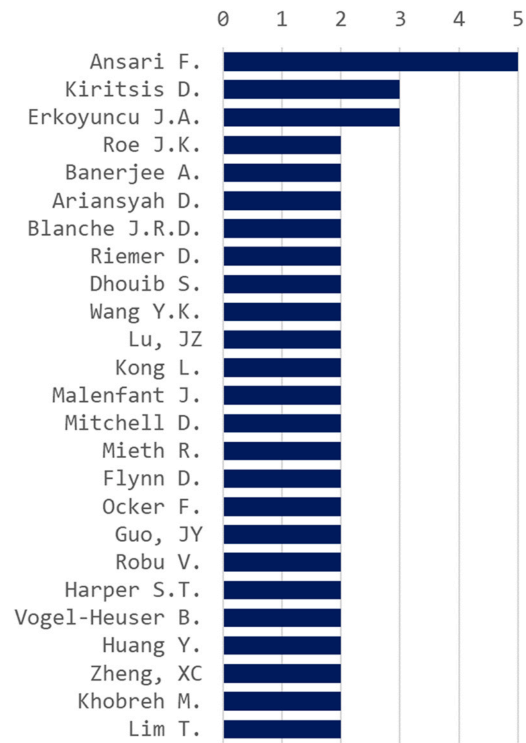

Fig. 9. List of authors having two or more articles within the final selection.

- In *food*, an article about semantic digital technologies for cost evaluation in the diary sector.

Characteristics

Results concerning the characteristics category can be divided into five subcategories (purpose, communication, representation, computation and microservices) as described in the previous

Table 6
List of conference names.

Conference name	Ref.
2017 22nd IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)	[46]
2019 IEEE 17TH International Conference on Industrial Informatics (INDIN)	[47]
2019 IEEE 28TH International Symposium on Industrial Electronics (ISIE)	[48]
2020 IEEE 6th International Conference on Computer and Communications, ICCC 2020	[49]
2021 26th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA)	[50–52]
2021 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM	[53]
2021 IEEE Intl Conf on Dependable, Autonomic and Secure Computing, Intl Conf on Pervasive Intelligence and Computing, Intl Conf on Cloud and Big Data Computing, Intl Conf on Cyber Science and Technology Congress (DASC/PiCom/CBDCom/CyberSciTech)	[54]
2021 International Conference on Indoor Positioning and Indoor Navigation (IPIN)	[55]
20th Congress of IABSE, New York City 2019: The Evolving Metropolis - Report	[56]
CEUR Workshop Proceedings	[57–61]
Communications in Computer and Information Science	[62]
DAI-SNAC 2021 - Proceedings of the 2021 Descriptive Approaches to IoT Security, Network, and Application Configuration	[63]
IECON Proceedings (Industrial Electronics Conference)	[64]
IFAC PapersOnLine	[65]
IFIP Advances in Information and Communication Technology	[66]
Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)	[67]
Procedia CIRP	[68]
Proceedings - 15th Annual International Conference on Distributed Computing in Sensor Systems, DCOSS 2019	[69]
Proceedings - 2017 IEEE 19th Conference on Business Informatics, CBI 2017	[70]
Proceedings - 2018 IEEE International Conference on Big Data, Big Data 2018	[71,72]
Proceedings - 2021 4th IEEE International Conference on Industrial Cyber-Physical Systems, ICPS 2021	[73,74]
Proceedings of 2021 14th International Conference Management of Large-Scale System Development, MLSD 2021	[75]
Proceedings of the 2017 ACM Web Science Conference (WEBSCI '17)	[76]
Proceedings of the Annual Offshore Technology Conference	[77]
Proceedings of the ASME 14TH International Manufacturing Science and Engineering Conference, 2019	[78]
WIT Transactions on the Built Environment	[79]

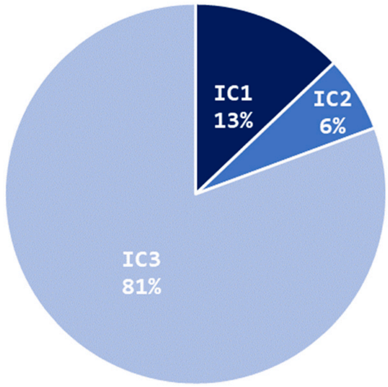

Fig. 10. Distribution per IC of the reviewed articles.

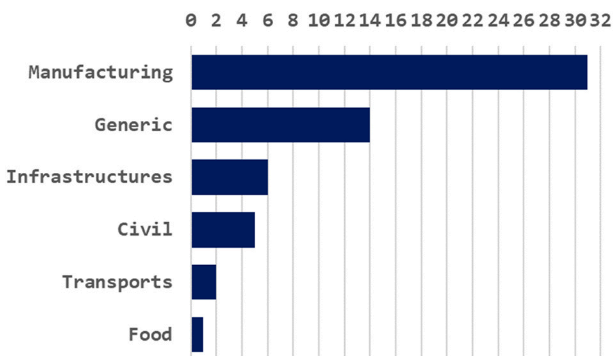

Fig. 11. Distribution of the reviewed papers per field of application.

methodology section. Following the description of the results for each subcategory with the classification that can be found in Fig. 5**.**

Purpose of the DT

The three aspects highlighted in this review concerning the purpose are the definition of the DT, the life cycle stage, and the rate at which the DT works.

Concerning the definition of the DT, most of the publications adopted the one used in the white paper of Michael Grieves, which is defined simply as *a virtual, digital equivalent to a physical product* [17]. All the other definitions that have been found in the publications were collected in Table 7.

In the life cycle stages, the main part of the life cycle where the DT has been implemented has been reviewed. Although this review focuses on the maintenance part, the DT should consider the whole life cycle, from the conceptualisation to the end of life. Fig. 13 shows the focus of the reviewed papers per each phase of the life cycle. The consideration of a wider DT, which considers the whole life cycle, allows feedback from the Operation and Service (O&S) stage to the concept or the design stage of the life cycle, ensuring the optimisation of the overall system through life.

Concerning the operational rate at which DTs operate in the reviewed articles, 22 papers out of 59, explicitly mentioned the fact that the data collection rate has been performed in real-time.

Although real-time operation rate is widely used and considered, the authors do not consider the real-time feature mandatory for a DT. Especially for assets that cannot be always connected to the network, such as planes, ships, helicopters, etc.

The last factor checked in this subsection was whether the reviewed papers were dealing with DT or CPPS. It has been found that 84% of the papers dealt with DT and the remainder 16% dealt with CPPS.

Communication

In this subsection, communication protocols and DT architectures will be reviewed. The OSI Open Source Interconnection (see ISO/IEC 7498 [80]) is a well-established network communication reference model proposed by Zimmermann in 1980 [81]. A brief description of how this model works will help the reader to better understand the next classification based on communication protocols. The OSI is a seven-layer model that allows defining any communication between two or more machines (broadcast or unicast). The seven layers are *physical*, *data link*, *network*, *transport*, *session*, *presentation*, and *application*. In Fig. 14 the structure of the OSI model is shown, in the same figure, the path of information either as receiver or sender is also illustrated.

For example, going from the top to the bottom of Fig. 14 is the case where a machine wants to send information to another machine in the network (e.g., a HyperText Transfer Protocol - HTTP request).

The first step happens in the *application* layer, which is the link between the application and the communication model. This is especially useful for those applications that are not network-aware.

In the next step, inside the *presentation* layer, the information is converted into raw data, which is readable from a machine (e.g., a text file converted into an SSL or ASCII file). The *session* layer checks the ports, both destination and source port, and adds them to the information for the next layer. The source port (PORT_S) comes from the application and the destination port (PORT_D) depends on the machine (e.g., In computers the first 1024 ports are known and fixed, port 80 is for the HTTP port, the web port). This layer connects the server to a client on a remote system.

The *session* layer checks the ports, both destination and source port, and adds them to the information for the next layer. The source port (PORT_S) comes from the application and the destination port (PORT_D) depends on the machine (e.g., In computers the first 1024 ports are known and fixed, port 80 is for the HTTP port, the web port). This layer connects the server to a client on a remote system.

The *transport* layer puts the SN (sequence number), in the information, because sometimes a big piece of information needs to be split into several small chunks numbered with an SN for connection bandwidth issues (e.g., SN = 1/20 means that this data is the first part of 20). The transport layer then has the function of disassembling the information, in the case of a sender, and assembling the information, in the case of the receiver. At this stage, the TCP (Transmission Control Protocol) segment is composed and is nothing but the string that contains PORT_S (source port), PORT_D (destination port), SN (Sequence Number), and "raw data".

The *network* layer has the functionality to append the IP_D (destination IP address) and IP_S (source IP address) to the information. The string is now called the IP (Internet Protocol) packet.

The *data link* layer checks the integrity of the information that is given from the FS (frame check sequence), which will then be appended to the information.

The *physical* layer appends the MAC (Media Access Control) addresses (MAC_D and MAC_S) to the information. After appending the MAC addresses, the whole information packet will then be sent to the network through the physical network board (e.g., the NIC - Network Interface Controller).

The path is mirrored in case the information is received, as illustrated on the left side of Fig. 14.

In the above-described process, the information string has been simplified describing only the main parts of typical information, in order to make it understandable. Modern computers do not follow the OSI model but follow the TCP/IP model. The latter is a four-layer model which can perfectly replace the former. The analogy between the two models can be seen in Fig. 15. Hypothetically, we can replace the OSI model with the TCP/IP model in Fig. 14, and nothing will

Table 7
List of definitions of DT found in the reviewed articles in chronological order.

Definition	Ref
"Digital Twin models are computerised clones of physical assets that can be used for in-depth analysis."	[76]
"The digital twin (DT) is a digital representation of a physical asset that can be used to describe its properties, condition, and behaviour through modelling, analysis, and simulation."	[25]
"Digital representation of an observable manufacturing element with a means to enable convergence between the element and its digital representation at an appropriate rate of synchronisation. (ISO 23247)"	[68]
"DT for buildings can be seen as BIM models extended to capture real-world data and feed it back into the model, thus neatly closing the information loop of asset lifecycle management."	[55]
"An integrated information flow that connects all the phases of the product lifecycle using accepted authoritative data sources (e.g., requirements, system architecture, technical data package (TDP), three-dimension (3D) CAD models)."	[52]
"The DT is an exact digital replica of something in the physical world."	[23]
"An integrated plant model 'maintained and kept consistent throughout the entire life of the plant' is a DT."	[42]
"DT is a digital representation of a real physical asset that represents the relevant features of the real asset within a model."	[60]
"DT is a digital copy of a physical asset that accurately represents and alters the asset state and behaviour within a certain context."	[75]
"An (ideal) digital twin is a virtual representation of an asset and like a monozygotic twin it shows the same behaviour and development as the asset."	[37]
"Digital Twin (DT) is the combination of logically integrated models of a physical asset to give useful insights using data associated with those models."	[43]

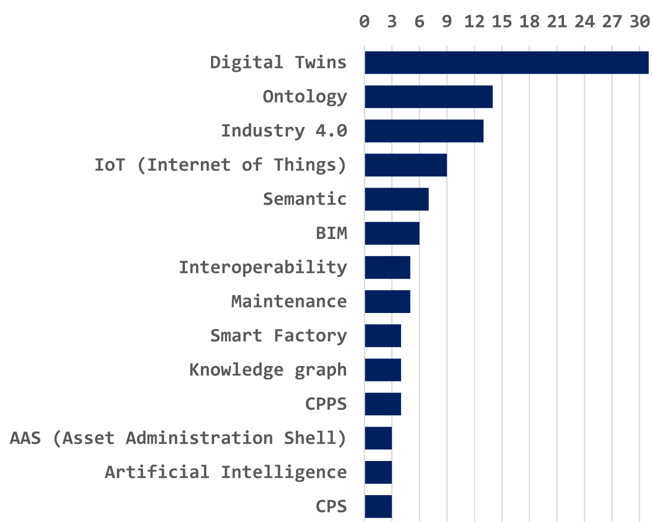

Fig. 12. List of keywords used at least 3 times in the reviewed publications.

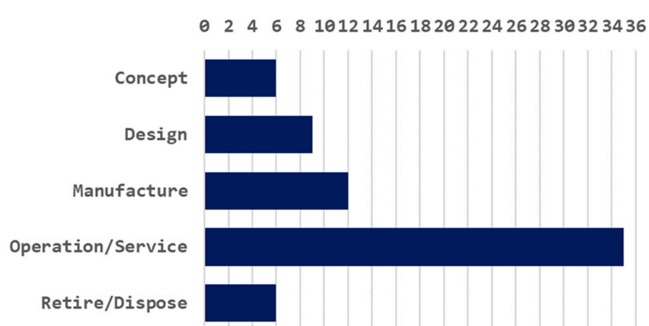

Fig. 13. Stages of the life cycle where reviewed papers had more focus.

change in the communication path. We just must consider that in the TCP/IP model, the physical layer works as the physical and data link layers of the OSI model, and the application layer works as the session, presentation, and application layers of the OSI model.

Having explained that, the classification in terms of communication protocols used, becomes easier to understand, and the results can be seen in Table 8. The table shows the 5 protocols used within the reviewed papers.

Concerning the architecture of the DTs in the reviewed articles, most of the proposed architecture models were found to be similar to the original model proposed in [82] by Michael Grieves. He initially defined a DT with 3 layers; the physical layer, the digital counterpart, and the data exchange layer between the two. Just 3 papers present a 4-layer architecture [33,35,78], and one presents a 6-layer architecture [75].

Knowledge representation

In this subsection, semantic capabilities, database and knowledge graph used, and data formats will be reviewed.

All the 59 reviewed articles implemented a semantic aspect in their digital platform. In particular 28 of them mentioned specifically about an ontology implementation. Only 5 out of these 28 referred to an application ontology referred to a top-level ontology (TLO), which explanation will follow in the conclusion section. 9 of these 28 papers have explicitly indicated the tool used to create and manage the ontology, which[1] is Protégé . In [70] has been also explicated the use of HermIT as a reasoner for ontology. HermIT is a reasoner for ontologies written using the Web Ontology Language (OWL).

Interoperability was also one of the key elements in some of the reviewed papers. To improve interoperability, some of the papers implemented a standard terminology, which allows for adopting a shared vocabulary and consequently an easier interpretation of the taxonomy exploited. In order to do that *standard ontologies* or *international standards* have been applied. Semantic Sensor Network (SSN) Ontology has been employed in 3 papers [28,44,61], while [70] used a taxonomy from ISO 2041, ISO 13372, and ISO 17359:20. In [75] has been used a taxonomy from IEC61968, IEC61970, and IEC 62325 CIM. An alternative solution to improve interoperability was the employment of standard architecture. With this respect, 5 papers [34,37,51,64,73] exploited RAMI 4.0, the well-known Reference Architecture Model Industrie 4.0 developed by the German Electrical and Electronic Manufacturers' Association (ZVEI) to support Industry 4.0 initiatives [84]. The exchange of information is enabled through the concept of Asset Administration Shell (AAS) used to describe an asset in a standardised manner [85].

Concerning databases, 3 different kinds of databases have been found, relational, non-relational, and graph database (also known as knowledge graph). Respectively 6 papers employed relational databases, 3 papers non-relational databases, and 15 papers graph databases. The main difference between a relational and a non-relational database is the structure, the non-relational database doesn't rely on a predefined structure. Among the relational databases, MS SQL, MySQL, MS Access, and SQLite 3 have been found. MongoDB and Elasticsearch for the non-relational, or NoSQL, solutions. Concerning the graph databases, GraphDB, Neo4J, and Apache

[1] https://protegewiki.stanford.edu/wiki/Main_Page

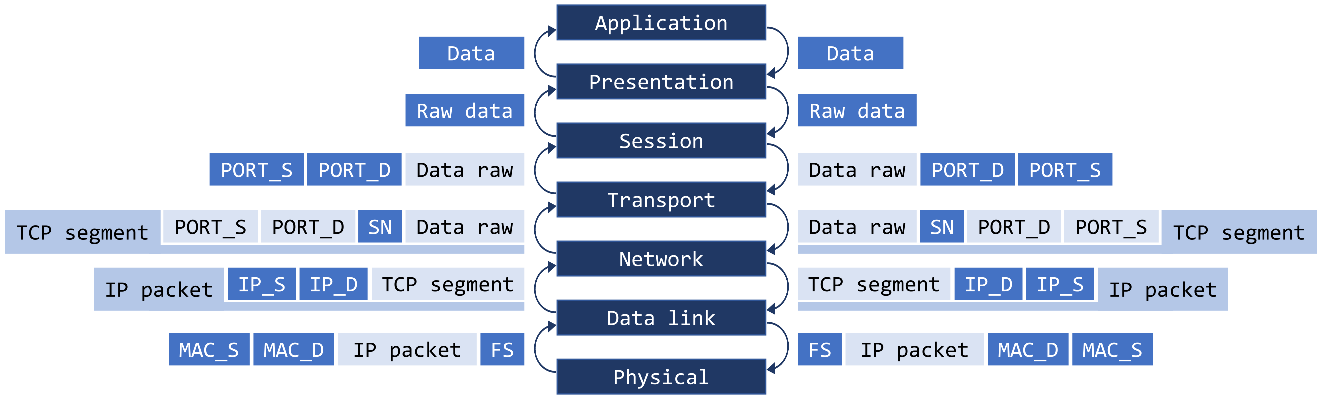

Fig. 14. Example of the machine to machine (M2M) communication with the OSI model. The left side shows how a machine receives information from another machine (receiver) and, on the right side, how a machine sends information to another machine (sender) [81].

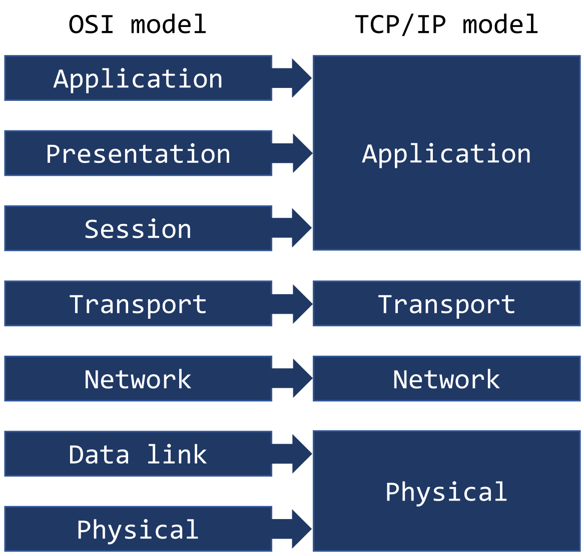

Fig. 15. Comparison between OSI 7-layer model and TCP/IP 4-layer model.

Jena were the solutions found in the reviewed articles. These solutions use different query languages, SPARQL for GraphDB and Apache Jena, while Cypher for Neo4J. The query language is in general the query language used to query the databases. The use of one kind of database doesn't exclude the employment of the others. Indeed, it would be possible to use more than one kind of database within the same DT.

Table 9 shows a classification of the data formats found in the reviewed articles. In the table can be also found a brief description for each data format. From the analysis emerged that OWL and RDF are the main data formats exploited, this is due to the employment of the semantic approach and knowledge graphs.

Computation

Computation starts with the selection of the storage engine. This can be local, as in the case of *edge computing*, or remote, as in the case of *cloud computing*.

Cloud computing allows the use of data storage and/or computing power on demand and remotely. Edge computing instead, brings storage and computation close to the location where it is needed. Both cloud computing and edge computing can coexist within the same system, Cloud computing is not always the best choice if we consider isolated systems such as ships or aeroplanes, which cannot be easily connected to a network. For these kinds of isolated systems, probably edge computing can be a better solution.

From the analysis of the articles, 5 out of 59 specifically mentioned the storage location. 3 articles adopted a hybrid approach (both cloud and edge computing) [34,37,73], while [30] explicated the use of cloud computing and [23] explicated the implementation of edge computing.

In 7 publications the exploitation of the REST-API interface implies the presence of the middleware [21,24,28,44,57,70,73]. In 4 publications [30,50,57,77] ROS (Robot Operating System) has been used as middleware, while Erlang middleware has been employed in [47] and a Java solution in [70].

Microservices

This section contains the results of the collection of the major modelling and simulation tools, visualisation and virtualisation tools that have been reviewed. Table 10 lists the tools used in the reviewed publications.

Table 8
Communication protocols in the network architecture for the DT.

Data exchange protocol	Description	Ref.
TCP/IP	TCP/IP (Transmission Control Protocol / Internet Protocol) is one of the most common communication models used among network devices.	[44,47,78]
TCP/UDP	Both communication protocols are based on the transport layer. The difference between TCP (Transmission Control Protocol) and UDP (User Datagram Protocol) is that the latter is not connection-oriented (connectionless) and prioritises time over reliability.	[57]
OPC UA	In OPC UA (Open Platform Communications United Architecture) the communication occurs at the TCP level. It is a machine-to-machine (M2M) communication protocol used in industrial automation environments. It can use either client/server or publish/subscribe pattern.	[24,37,51,64]
MQTT	MQTT (Message Queuing Telemetry Transport) is an open publish-subscribe network protocol – BS ISO/IEC 20922 [83]. It allows communication between devices usually over a TCP/IP model in the application layer.	[38,44,57,73]
HTTP	HTTP (HyperText Transfer Protocol) is an application layer protocol (the higher layer for both OSI and TCP/IP model). It is a request-response protocol in a client-server pattern.	[21,57]

Table 9
Classification of data format found in the reviewed articles.

Data/file format	Description	Ref
CSV	CSV (Comma-Separated Value) is a text-based file format used for the import and export of data in tables (e.g., databases). Each value is separated through a predefined separator (e.g., comma).	[77]
IFC	IFC (Industry Foundation Classes) is a data model used to describe construction industry data. IFC is a platform-neutral, open format, and object-based file format developed to ease interoperability specifically in the construction industry. ISO 16739-1:2018	[22]
JSON	JSON (JavaScript Object Notation) is a lightweight open standard file format for storing and transporting data. It is intuitive, easy to read and write, works across platforms and is used as a data-interchange language.	[21,32,57,63,73]
OWL	OWL (Web Ontology Language) is a markup language for explicitly representing the meaning and semantics of terms and relationships between them. OWL was developed by the W3C consortium based on XML and is a computational logic-based language such that knowledge expressed in OWL can be exploited by computer programs.	[24,28,37,43,45,51,52,59,61,64,70]
RDF	The RDF (Resource Description Framework) is the basic tool proposed by the W3C consortium for encoding, exchanging and reusing structured metadata and enables semantic interoperability between applications sharing information on a network.	[23,24,28,42,45,46,53,69,70,72]
XML	XML (Extensible Markup Language) is a markup language that defines a set of rules for encoding data. It is a software/hardware-independent tool for storing and transporting data.	[21,23,35,47,53]

https://www.w3.org/OWL/

Conclusion elements

In this section, the benefits of using DTs were gathered, along with major findings, limitations, and future works from the reviewed articles. All the conclusions were summarised and grouped into broader concepts. Major findings are not interesting for this review, because they regard specific findings for particular applications, but benefits, limitations, and future works can be interesting for all use cases.

The benefits of using DTs found in the reviewed articles can be summarised in the following points:

a) Minimise the damage growth
b) Enable fault prediction
c) Enable proactive maintenance
d) Enhance the capability of interconnections of different systems and the integration in a wider environment
e) Increase the information available to help analytics
f) Enable a long-term vision to apply a cost-effective maintenance strategy
g) Reduce downtimes, increase operation
h) Increase overall efficiency and reliability

The limitations gathered can be summarised in the following points:

a) High initial costs
b) Management of large dataset
c) Lack of automatic feedback correction in previous phases of the life cycle, to improve production
d) The gap between as-built and as-is condition
e) Lack of guidance in the implementation
f) The need for specific and dedicated solutions
g) Unknown green performance evaluation
h) Lack of stakeholders' awareness within the same supply chain.

Finally, future works proposed are summarised as follows:

a) Application of the proposed methodology in a real case
b) Expand the range of damage to monitor
c) Consider cloud and/or edge computing
d) Find and fight the source of degradation
e) Enable real-time monitoring
f) Try the same method in different fields, check flexibility
g) Provide feedback to improve the design and production phase
h) Analyse the value of having a higher-level DT that contains sub-level DTs
i) Perform a sustainability evaluation
j) Improve accuracy, refine DT for specific applications
k) Balance costs and benefits
l) Create structured knowledge for the O&M (Operation and Maintenance) phase
m) Consider a DT for the whole life cycle

Table 10
List of tools employed for modelling and simulation, visualisation, and virtualisation.

Tool	Ref.
Autodesk Revit	[28]
Eclipse Papyrus	[51,64]
Halve	[70]
Inversiv	[70]
JavaScript	[70]
Python	[24,50]
StreamPipes	[71]
Unity	[50]
VoluSoft	[32]

Characterisation of a DT for maintenance and health management

In this section, a general characterisation of a DT for maintenance and health monitoring has been proposed. The following subsection presents the DT concept and its evolution and the conceptual model of the DT for maintenance.

DT concept evolution

The DT concept was first introduced by John Vickers over a model created by Michael Grieves in 2003 at the University of Michigan's Executive Course on Product Lifecycle Management (PLM) [82]. The term first appeared on page 133 of the book *Virtually Perfect: Driving Innovative and Lean Products through Product Lifecycle Management* [86]. The conceptual DT model was composed of three main parts: the real space, the virtual space, and the data exchange space between the two [82]. The conceptual model derived from the white paper is shown in Fig. 16.

The definition of DT given by Grieves and Vickers in 2017 is the following: "*the DT is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its DT*" [18].

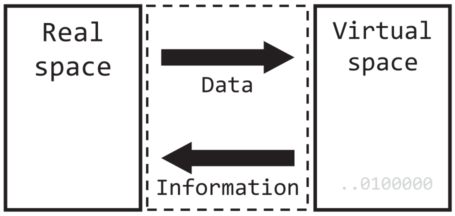

Fig. 16. Initial conceptual model of DT, inspired by M. Grieves.

The main reason why the DT concept rose was to move the work activity into the virtual space, perform all tests on a fidelity digital counterpart, see errors, correct them, and once ready, transfer the information back to the physical item.

To have a higher value from it, the DT must be supported and fed over the whole life cycle. To cover this need, Grieves divided the DT into three types that operate together in a DT Environment (DTE): the DT Prototype (DTP), the DT Instance (DTI), and the DT Aggregate (DTA) [87].

DTP is used to describe prototypical physical assets containing information about the early stage of the creation of the physical artefact. DTP covers *all products that can be made.*

DTI is used to describe a specific corresponding physical asset, to which the DT will be linked throughout life. DTI covers *all products that are made.*

DTAs are the aggregation of all the DTIs. The first value is to correlate previous state changes with subsequent behavioural outcomes. This enables, for example, the prediction of component failure when certain sensor data predefined thresholds are met. The second value can occur via a learning process when a small group of DTIs learn from actions. That learning can be conveyed to the rest of the DTIs. DTA covers *all products that have been made.*

The three DT types can be applied in several phases of the asset life cycle. DTP can be applied in the concept and design phase. Consecutively, DTI can be added in the manufacturing phase, and eventually DTA in the operation and service (O&S) phase till the retire/dispose phase. Fig. 18 would highlight the two different routes of the physical and information life cycle, while the physical is an open cycle most of the time, the information life cycle would be closed. Valuable information mostly from O&S and disposal phases can be useful to improve the initial phases of successive assets. As in Fig. 17, in the Grieves model, the feature of the DT to bring back information from later stages of the life cycle to early stages of the other asset's life cycle is one of the most precious added values of using this technology. Product Life cycle Management (PLM) feedback loops, were introduced by Grieves in [88], and their basic principle is using information from each phase of the life cycle to improve the design and creation phase of the assets.

All the above considerations let us think about a world of interconnected twins, where the DT of a system can be composed of a system of smaller connected DTs. Where a DT can learn from the experience of similar DTs in other environments, the interoperability and integrability of such platform thus creating a network of twins.

Difference between DT and model

In many cases, the difference between DT and model is not made clear, mostly in the early stages when approaching DT technology. Wright and Davidson pointed out that the DT concept gathers several existing technologies, and explained that a model is part of the DT. A model is mostly a static representation of an asset, but for those assets that change over time, the model would not be valid anymore. For those assets, it is worth using a DT paradigm that follows the assets throughout their life [89]. A DT thus adds context and time dimensions to the overall representation of the asset which is merely a static model at the outset.

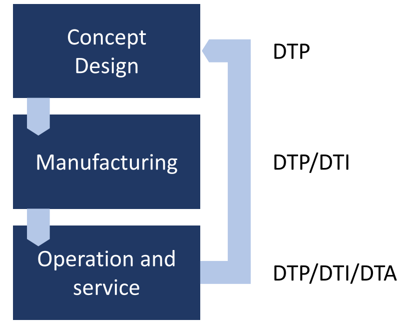

Fig. 17. Distribution of DT types through the life cycle and information flow.

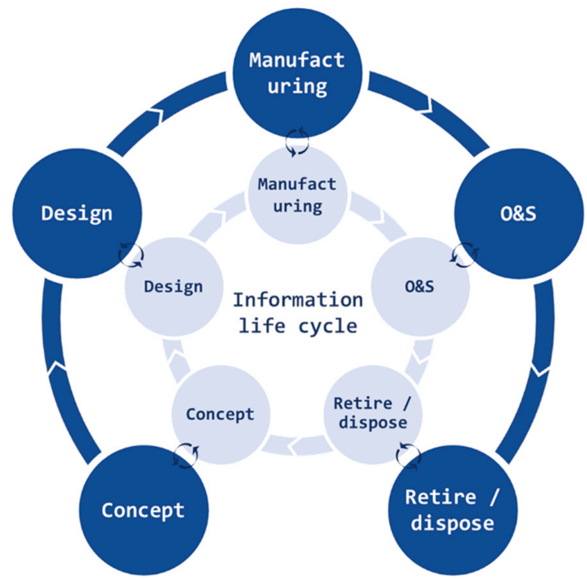

Fig. 18. Physical asset life cycle and information life cycle.

Kapteyn et. al. pointed out that *differences in material properties, manufacturing processes, and operational histories are just some of the many factors that ensure that no two engineering systems are identical, even if they share the same design parameters* [90].

Therefore, modelling many similar assets using a single model neglects those above-mentioned differences. The DT paradigm aims to overcome those differences by providing an adaptive, comprehensive, and authoritative digital model tailored to each unique physical asset [90].

Difference between DT and BIM

Building Information Modelling (BIM) has been revolutionary for the construction sector as it brings in a single digital platform that incorporates all the physical and functional characteristics of the building project, which were previously siloed. However, BIM does not provide a complete solution for whole-life asset management, since it is a model and as said before, a model is not the perfect representation of an asset that changes over time, as a building does. *From the perspective of information richness and analytical/decision-making capability, the concept of Digital Twins (DT) is broader than BIM* [91]. DT is a more comprehensive solution to monitor the as-is condition of a building. Moreover, a DT integrates data analytics, control and simulation functions that allow maintainers to improve service plans [92].

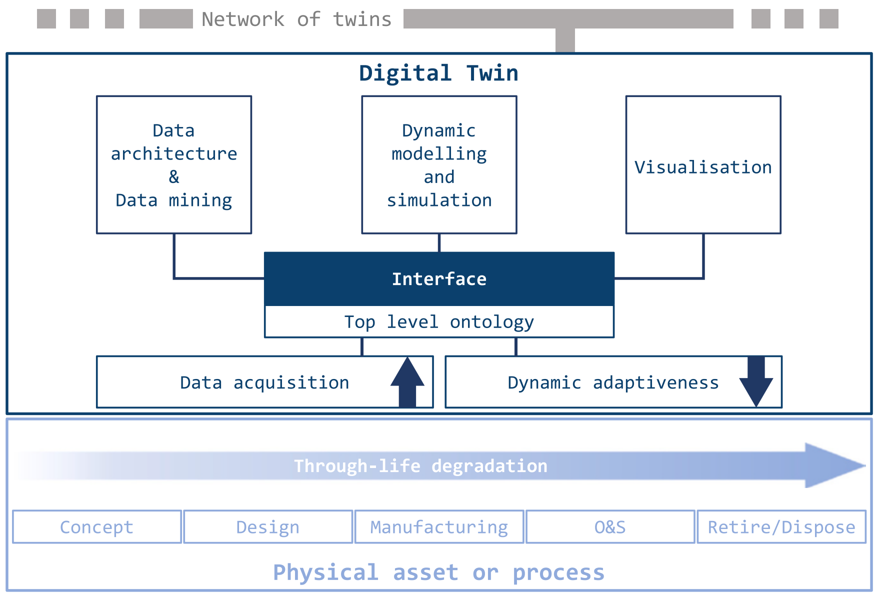

Fig. 19. DT conceptual model characterisation.

DT characterisation

Fig. 19 shows the representation of the conceptual model for a DT for degradation assessment. On the bottom end, in light blue is the physical space (the real space), which represents the through-life degradation of an asset or process. Above this, in dark blue is the virtual space, which represents the main components of a DT. Physical and virtual spaces are connected via data and information. Data acquisition goes from the physical world to the real world; information, instead, acts as dynamic adaptiveness, from the digital world to the physical world. Four main blocks constitute the essential functionalities of the DT.

DT ontology and taxonomy of degradation is the first block, where the dictionary of the DT will be developed. This is to give the DT context awareness. Ontology is very important because if chosen right, it enables effective DT interconnection and the creation of the network of twins. The ontology must start from a domainless top-level-ontology. This review found that several upper-ontologies exist and have been presented in the work from the centre for digital built Britain (CDBB) [93]. This review identified a variety of fundamentals ontologies such as BFO (Basic Formal Ontology), BORO (Business Objects Reference Ontology), and DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering), etc. Concerning the BFO, there is currently a draft version of an ISO standard (ISO/IEC 21838, which has been published in 2021). Choosing a standard would be useful because it allows the DT developer to start with the same top-level ontology. Using the same top-level ontology enables the integration of the DT in a complex system composed of other DTs even belonging to different field domains. This is because all the DTs use the same dictionary and can easily talk with each other allowing the creation of a DT for an entire company, or the DT for a city, containing lower-level DTs. All of this has already been implemented successfully, specifically: in medicine with the implementation of the gene ontology (GO) [94]; and on the internet where a unique web semantic has been chosen.

The data architecture & data mining component forms the second block that relies on the ontology chosen in the previous block to create the data structure of the DT and the optimal mining strategy.

Data modelling and simulation become the third block that in essence is the brain of the DT. Here the DT can use the data to predict behaviours of the physical asset or simulate several scenarios to choose the best configuration for the physical asset. Artificial intelligence algorithms can help the DT to better predict failure learned from the previous patterns. This block could also be connected with other blocks creating the twins' network, or rather the network of twins.

Visualisation, the fourth block and final component, enables the visualisation of the results or in general provides a graphical interface for the user to interact with the DT. This can be not only an application or a web app but also the graphical environment used in virtual reality (VR) or augmented reality (AR).

Interface, the central block, represents the cornerstone of the information exchange of the DT. It allows the DT to talk with different modules, managing all the inlet and outlet information to enable the DT to work regardless of the system where it will be applied.

Maintenance and DT

A previous version of the conceptual model of DT to monitor through-life degradation has been already published by the authors in [95], which contains theoretical justification for using DT for maintenance purposes. However, recent studies might empower the advantages of using DT for maintenance. Bevilacqua et al. [96] highlighted how a predictive maintenance DT prevents high-risk events for operators. Aivaliotis et al. in [97] implemented degradation models in the DT that can be used to calculate the RUL of components. This also improves the decision making strategy and production planning [98].

In general, DT used for maintenance can lower costs [99], improve the accuracy of predictions [100–102], and make the manufacturing system more sustainable, reliable, and efficient [103].

From DT to CT

Recent literature indicates that there is an ongoing interest, especially in the association of semantic technologies and DTs, particularly combining ontology with DTs. Boschert et al. [104] called the next generation Digital Twin (nexDT) the DT that enables interconnectivity of systems using semantic technologies, like ontologies. Akroyd et al. [105] introduced the concept of Universal Digital Twin, a digital twin that uses a dynamic knowledge graph to facilitate cross-domain interoperability for DTs. Lu et al. [9] presented the Cognitive Twin (CT) concept as a DT with augmented semantic capabilities to support internet of things systems or decision-making in manufacturing systems [106]. Li et al. [107] implemented the cognitive twin concept to support the co-simulation of complex engineering assets, which consists of the combination of different digital tools. Abburu et al. [108] created COGNITWIN software toolbox for the process industry and considered the CT as an evolution of the Hybrid DT (HT), which itself has been considered an evolution of the standard DT. Although considered relevant for this research, the authors did not include CT in the systematic analysis because of the novelty of this terminology. On the Scopus database, considered for this review, CT's papers started to be available just from 2020. To date, 5 papers have been published on the engineering subject [9,106,107,109,110].

Conclusion

This paper presents a thematic review and characterisation of DTs in terms of technology used, applications, and limitations in the context of maintenance and degradation.

Concerning the first research question: *How DTs for the maintenance phase of the life cycle are developed?* Conducting the SLR enabled a systematic and reproducible methodology to classify and review information about DTs related to the maintenance field. Randall [111] divided maintenance into three phases of the Prognostics and Health Monitoring (PHM) process: detection; diagnostics, and prognostics. A DT should be able to satisfy each of these PHM steps.

Today's maintenance issues can be summarised in two main categories. The first issue is that maintenance today is mostly reactive, reaction once a failure occurs, or planned preventive when periodic maintenance is planned to prevent failures. This causes unexpected downtimes and unnecessary maintenance. The second issue is that departments within the same supply chain and even within the same company are siloed. They don't share data and information across the supply chain. This will cause a loss of a lot of important information and knowledge about the system.

Early detection of faults, e.g., cracks or corrosion, has the potential to greatly reduce the through-life maintenance costs of complex systems and may help prevent unexpected breakdowns. This can be achieved using the DT paradigm. Using a DT to monitor the health of those systems will help the transition from time-based maintenance to condition-based maintenance, avoiding the waste of working components or waste of time. DT has always existed, just called by different names, the novelty of the DT concept is to break the walls of each department, where information has been siloed so far.

The second research question: *How can be characterised a DT for maintenance?* In the last subsection of the Results section, a characterisation of a DT for degradation assessment has been presented. A DT should be able to be integrated into a network in a system of system scenario. This particular scenario identifies the *federation of twins*. This can be achieved by implementing a common semantic approach over the network, such as adopting a single top-level ontology. A DT must rely on a solid structure and contain modelling and simulation tools that use artificial intelligence (AI) algorithms to predict the remaining useful life (RUL) of the components within a system. A DT can collect data in real-time or can collect data when needed, depending on the operation of the asset. Assets that are not always connected to a network can discretely exchange information. We want to call this data transmission rate capability of a DT *in-time*. A DT can have the computational power either on-site (e.g., edge computing), or off-site (e.g., cloud computing).

High importance is the capability to be interconnected in a network of twins, which will enable, for instance, the DT integration across different sectors and different stages within a supply chain. Emphasis has been given to this interconnection capability that enables the real added value of using the DT paradigm. The same that allows the medicine to today's progress, through to the worldwide adoption of the gene ontology (GO); or the development of the internet through to the adoption of the Web semantic.

The limitation of this review is due to the non-standardisation of this technology. The search string can be improved to include other studies that do not use one of the words used for this article. There are still research projects that might approach similar topics, naming DT differently (e.g., virtual twin, digital thread, digital replica, surrogate, etc.). Additionally, the degradation topic is wide, research projects may consider degradation topics without using the general words used in this review. However, several initial trials have been performed before reaching this search string, considering the string used, and its suitability for this review.

As previously anticipated, in the last 2 decades the medical industry has made leaps and bounds, and part of the credit goes to the adoption of the ontological approach, particularly the top-level ontology (TLO). In fact, the creation of the Open Biomedical Ontology (OBO) foundry in 2002 has made a significant impact on the industry as a whole. The OBO Foundry is a collection of all the biomedical ontologies, including GO, based on the same reference TLO, which is nothing but the BFO itself [94]. This approach improved the interconnection of different ontologies as it provided a domain-neutral TLO as a starting point to develop domain-specific ontologies. This also gave the possibility to reuse and expand existing ontologies, instead of creating them from scratch without following any structured methodology.

In 2016, at the National Institute of Standard Technologies (NIST), a mixed group of researchers and industry experts created the Industrial Ontology Foundry (IOF) that reproduces the idea of the OBO foundry for the manufacturing sector [32]. They also selected BFO as the reference TLO for the IOF. BFO is currently in the final phase to become an ISO standard, ISO/IEC 21838-2.

Future works will be focusing on investigating the TLO for the development of DTs, and evaluating the advantages and limitations of this approach. Exploring the opportunities that could give a structured DT architecture, such as the one proposed in the previous section of this review, could potentially provide an opportunity for manufacturing industries to replicate the same successes that this approach brought to the biomedical sector. Developing structured DTs based on a standardised TLO, such as BFO, might improve the interconnections, enabling the creation of a network of twins or a federation of twins. The structured DT we presented in this paper can be also considered a cognitive twin, which we are going to develop using BFO as TLO. There are already other examples in research, such as Rozanec et al. [110] that presented the model of actionable CT based on BFO. The network of twins might provide a larger training dataset for the artificial intelligence installed in the twins, and this can improve the experience and hence the predictions of the twins. Moreover, in a future human-machine interaction scenario, where both humans and machines will have a DT, it is envisaged that the human DT will likely be based on BFO, a TLO. The review has also shown string evidence that BFO is already the reference TLO for the biomedicine sector. Therefore, a machine CT based on BFO will easily exchange information with human CT and vice versa. In general, the TLO-based CT could be the answer to the need, highlighted in the introduction, "*to have a unique digital framework able to break down silos*".

Data availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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