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Comprehensive Systematic Analysis of Digital Twins: History, Concepts, Development, Applications, Challenges, Gaps and Future Work

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Abstract*— Digital Twins (DTs) continue to evolve, continuously increasing the variety of definitions of DTs in the literature, resulting in misconceptions and confusion. To date many reviews on DTs, but none provide a comprehensive analysis of the DTs' technologies; Therefore, there is a need to consolidate a comprehensive research analysis of the DTs technology to maintain a common and shared understanding of the technology and ensure that future research efforts are based on a solid foundation. The literature states that DTs can be applied to any application; however, there is a lack of integration of actual DTs in most industries; Therefore, there is a need to identify what is still missing to make DTs technology compliant with its description in the literature. Many approaches have been proposed to design and implement DTs to date; however, most, if not all, of them lack a comprehensive examination and analysis of all techniques and methods used to maximise the benefits of DTs. This paper; (A) Comprehensively analyses the DTs technology by incorporating the science mapping method for the first time. (B) Deeply examine DTs' concept, maturity, creation, values, applications, techniques, and technology to identify the most suitable way to implement DTs. (C) Guide the status of DTs development and application in today's academic and industrial environment. (D) Consolidate the different types of DTs throughout the literature to easily identify DTs from the rest of the favourable terms such as 'product avatar', 'digital thread', 'digital model', and 'digital shadow'. (E) Proposes a generalised concept that encompasses the breadth of options available and provides a detailed characterisation which includes criteria to distinguish the Digital Twin from other digital technologies "Digital Twins are a live virtual replica that continuously simulates the entire mechanical behaviour of anything".

***Keywords*— Digital Twin, Internet of Things, Machine Learning, Artificial intelligence, and Remote Condition Monitoring.**

I. INTRODUCTION

Digital Twins (DTs) have transformed the Industrial Revolution, highly detailed virtual replicas of machinery or systems. Many businesses already use DTs to detect defects and improve efficiency. As information technologies advance, the digitalisation process accelerates, particularly with the emergence of a new generation of information technologies (New ITs) such as the Internet of Things (IoT), cloud computing, big data analytics, and Artificial Intelligence (AI). They were divided into four stages: digital enablement, digital support, digital control and linkage, and cyber-physical integration. Many consider John McCarthy's 1956 "Dartmouth Summer Scientific Project" workshop on AI the official introduction of AI as a research topic [1]. Since 1956, artificial intelligence research has yielded intelligent systems capable of performing physical tasks, reasoning, forecasting future events, and making decisions. Machine Learning (ML), Deep Learning (DL), the Central Processing Unit (CPU), Graphics Processing Unit (GPU), Tensor Processing Unit (TPU), and processing capacity have all aided in the widespread adoption of AI applications in our daily lives. NASA pioneered the "(Physical) twin" concept through system engineering and condition monitoring in 1970. For Apollo 13, two identical spacecraft were built, one of which was flown into space to complete the mission, and the other remained on earth. NASA used the one that remained on earth to investigate what was happening in space [2]. They recognised the DT phenomenon and immediately began investigating the technology's impact on business.

Michael Grieves made the first proposal to use the word "(Digital Twin)" in 2002; naturally, the notion was presented in the context of Product Lifecycle Management (PLM). According to [3] definitions, DT is a three-dimensional representation of the actual physical system: (A) physical entity, (B) digital counterpart, and (C) connectivity between the physical and digital worlds. On the other hand, Grieves' definition was not a formally defined term. Grieves classified his 2002 concept of DT into three categories in 2005, further subdividing it into three subcategories. DTs prototype (A) DTs aggregate (B) DTs instance (C) DTs instance. With the advent of industry 4.0 and IoT, data collection methods rapidly evolve from manual data collection on paper to digital data collection via sensing technologies, vision systems, image processing, laser, coordinate measuring machines, and actuators [4]. Physical measures are now digitally gathered, stored, analysed, and shown. The introduction of AI, ML, DL, CPU, TPU, GPU, and IoT laid the groundwork for the DTs, enabling visual monitoring, control, and optimisation of products [5].

In 2010 NASA characterised DTs in modelling, simulation, information technology, and a processing roadmap. Between 2005 and 2010, a spate of technology improvements occurred, and NASA and the US Air Force used DTs for the structural management of aircraft. NASA and the US Air Force selected the DTs as a critical and promising technology for future vehicles in a joint paper in 2012 [6]. Following this publication, many academic studies in aerospace and aeronautics were conducted to propose the Airframe DTs for design and maintenance. Grieves introduced the three-dimensional structural DTs [3], allowing many industries other than aerospace to begin using the DTs Researchers forecasted various concepts of DTs technology and integrated them into multiple technologies for a brighter future. On the other hand, substantial industrial conglomerates and well-known software companies (such as Parametric Technology Corporation) (e.g. Siemens). Academics and industry pioneered the DTs concept and began developing product and service business strategies. Service sectors include health care and medicine [7], automotive DTs Bring Value to Big RFID and IoT Data - RFID Journal, n.d.), and oil and gas [8] as examples of service industries. Lockheed Martin Company of Space Systems named DTs one of the top six promising aerospace and future defence technologies in 2017 [9]. In 2018, the official global research and advisory firm (Gartner) declared DTs one of the top ten promising future technologies [10]. DTs technologies have received widespread attention; however, despite significant work and discovery that promises a prosperous future in integrating DTs in industries, the state of the research is opaque [11]. The concept is not well understood, impacting the technology's future development.

1.1 Contribution

1. Provide a comprehensive systematic analysis of the DTs' technologies; for the first time, using a systematic review methodology while incorporating the science mapping method.
2. This paper deeply examines DTs' concept, maturity, creation, values, applications, techniques, and technology to identify and create the most suitable way to implement DTs in academia and industry through 230 publications.
3. This paper sets out to guide the status of DTs development and application in today's academic and industrial environment.
4. This paper also outlines the current challenges and possible future work directions.
5. This paper consolidates the different types of DTs and definitions throughout the literature to easily identify DTs from the rest of the favourable terms such as 'product avatar', 'digital thread', 'digital model', and 'digital shadow'.
6. This paper proposes a generalised concept/definition that encompasses the breadth of options available and provides a detailed characterisation which includes criteria to distinguish the Digital Twin from other digital technologies. The proposed concept/definition is "*Digital Twins are a live virtual replica that continuously simulates the entire mechanical behaviour of anything*".

1.2 Scope of the Review

The first stage in any review is to define the scope of the study in order to establish the study's restrictions, boundaries, and objectives. [12] specified six dimensions to be followed while deciding the scope of the review. The author of this research will determine the scope in line with[12] as follows:

Focus: Using this citation, the authors will direct the study's attention to the DTs' concepts, applications, methods, and findings. ***Aim:*** Regarding the second dimension, the authors conducted this study to discover limitations, gaps, and concerns that ultimately result in the inability to use technology accurately and correctly. ***Perspective***: This research's authors present the review objectively and without bias. ***Coverage****:* This review will be representative, and the authors are committed to ensuring that it covers all relevant areas to accomplish the purpose. ***Organisation****:* The organisation is conceptual and is determined by the scope and perspective. ***Audience****:* The author addresses this work to engineers, engineering academics, and technology scientists.

II. METHODOLOGY

Many articles and authors highlight the importance of carrying out the relevant review study in all scientific research [11]; to add new knowledge to the existing scientific knowledge. The related work review identified what work was done relative to the area of research. It is critical to avoid duplication of research and properly recognise the authors of prior work. This investigation began with the fundamental issues surrounding DT technology. The authors of this study proposed the initial questions that would serve as a guide for conducting the systematic review. In order to eliminate bias toward specific scientific publishers, additional sources such as Google Scholar were employed. The authors of this review consider this literature method appropriate and enough for this research in line with Webster & Watson 2002. Although the time was not strictly specified, the literature started in November 2019. The study focused on "DT", "IoT", and "CM" to reach the aim of the research.

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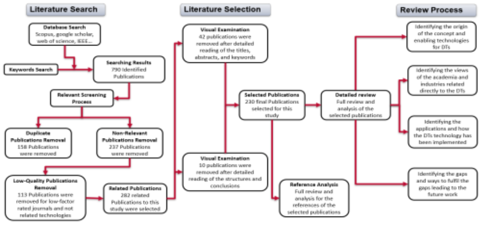

Figure 1. Shows an overview of the comprehensive systematic analysis process

This study used a systematic review, a crucial research component resulting in an overview of earlier research in a particular area of study and pointing out any knowledge gaps in the articles that have already been published [13], [14]. This approach abides by standards, including a systematic review or presentation of a transparent process, replication and updates, and summarising and analysing the research's major topic. This study modified the Refs' [15]–[17] methodologies to evaluate and review the substantial body of literature within the defined domain. An initial literature search using various databases, a filtration process, and content analysis are required. As a result, a thorough content analysis was done after selecting academic journal articles in three stages, choosing publications that were closely related to them.

2.1 Literature Search

Database Search: Since Scopus contains a wider selection of scientific papers [18], [19], it was chosen for the initial literature search. In addition, search engines like Web of Science, PubMed, and Google Scholar perform worse than Scopus [19]. [18] noted that compared to other databases, the Scopus database includes conference papers, has a quicker indexing procedure, and is available for more current publications. A thorough search was done using a two-parts. The first part of the search was a search string in the Scopus "article title/abstract/keyword" field. Keywords relating to "digital twin", "digital twins", "real-time condition monitoring", "internet of things", "virtual counterpart", or "digital replica" or "virtual twin" made up the first section. The time frame was established from 2000 to 2022. Additionally, "article", "review", "state of the art", and "literature review" were chosen as the document type since they represent the most trustworthy and influential sources of information [20]. The table below summarises the database used by the author to make sure the author is not biased in the selective methodology**.**

TABLE 1. Summary of the database used in the research

Database	Specifications
IEEE	"Title, Subject, Abstract"
Web of Science	"Title, Keywords, Subject, Abstract"
Google Scholar	"Title, Keywords, Content Item Title, Subject, Abstract"
SpringerLink	"Title, Keywords, Subject, Abstract"
Science Direct	"Title, Subject, Abstract"
AIS Electronic Library	"Title, Keywords, Content Item Title, Subject, Abstract"
EBSCOhost	"Title, Subject, Abstract"
Emerald	"Title, Keywords, Content Item Title, Subject, Abstract"

Searching Results: This search query brought up a total of 437 different papers for retrieval. After retrieving a small number of papers from Scopus, we expanded our search to include more databases, including ScienceDirect and Web of Science and others, as shown in table 2, which led to the discovery of 353 new publications. This expansion of database search was done to guarantee that an adequate number of research results on applying digital twins in the academic and industrial sectors were collected and evaluated. The total search results were 790 publications across academics and industries.

Articles Refinement: The first step is to collect good quality publications, and with practical screening through at least the last ten years, [21] identified further steps to refine the articles obtained. Removing duplicates: 158 Publications were removed for duplications; we retrieved a total of 632 publications, including journals articles and papers presented at conferences Non-Relevant Publications Removal: 237 Publications were removed. The last decade's publications worth in the study area were compiled, including articles, theses, and conference papers. However, industrial papers and commentaries will be eliminated due to the high quality of the publications collected. Low-Quality Publications Removal: 113 Publications were removed for low-factor rated journals and not related technologies after the author identified essential terms associated with the DTs, such as IoT and CPS, VR, AR, and CM; however not related to the DTs technology. Related Publications: 282 papers were obtained from various periodicals and conference proceedings spanning 34 different sources. The total number of citations received by each of the 282 publications is displayed in table 4; during the literature search phase where it was conducted. This method provides a measurement of the impact and influences the papers chosen for this exercise have had.

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2.2 Literature Selection

Visual examinations*:* Forty-two publications were removed after detailed reading of the titles, abstracts, and keywords. The primary goal of extensively examining the keywords is to ensure they meet the study's goals. Thus, when the databases returned 282 results when the keywords were used, the resulting articles were selected for further refinement and analysis. Ten publications were removed after detailed reading of the structures and conclusions

Selected Publications: Two hundred thirty final Publications were selected for this study.

2.3 Review Process

This step is independent of the publishing date and is focused on the selection benchmark. The author will disregard whether the work was published in the present or the past. Instead, the author will focus on the application and concept of DTs. This method emphasises the CM perspective. The benchmark is summarised into two steps; the first is Application and scenario optimisation, and the second is Providing a comprehensive analysis of trends to assess the DTs and framework.

Detailed Review: Complete and detailed review and analysis of the selected publications**,** Identifying the origin of the concept and enabling technologies for DTs**,** Identifying the views of the academia and industries related directly to the DTs**,** Identifying the applications and how the DTs technology has been implemented**, and** Identifying the gaps and ways to fulfil the gaps leading to the future work.

Reference Analysis: The reference analysis is the final stage; the initial reference for the closely related articles was 760; the further study revealed 30 additional publications. DTs and Condition Monitoring (CM) were then formed as categories for article analysis to fit and match the study's topic; ten additional references were added during the research to make the study more comprehensive and concrete.

Table 2: Shows the number of citations of selected articles

Item	Type	Ref	Google Scholar Citations	Scopus Citations
1	Article	[1], [5], [33], [35], [52], [116], [42]	12, 35, 42, 17, 27, 64, 58	38, 84, 63, 26, 74, 15, 16
2	Article	[21],[25], [2], [4], [6], [86], [44]	25, 27, 38, 49, 19, 62, 55	23, 42, 31, 13, 24, 7, 40,
3	Article	[7], [23], [11], [17], [20], [46], [34]	91, 63, 27, 47, 41, 53, 22	41, 21, 17, 31, 32, 25, 23
4	Article	[103], [47], [75], [65], [81], [188]	33, 16, 54, 24, 15, 37	17, 31, 17, 31, 27, 45, 14
5	Article	[203], [208], [161], [110], [154]	64, 43 ,52, 23, 43	13, 31, 11, 21, 16
6	Article	[14], [37], [44], [56],[101], [141]	26, 36, 77, 46, 42, 61	22, 62, 34, 57, 11, 33
7	Article	[67], [78], [76], [3], [87], [98]	40, 27, 25, 14, 18, 35	20, 37, 15, 13, 12, 15
8	Article	[61], [63], [79], [80], [62], [83]	11, 17, 31, 39, 48, 12	17, 27, 22, 31, 27, 26
9	Article	[121], [125], [133], [135], [152]	44, 61, 21, 5, 8	14, 21, 11, 25, 18
10	Article	[122], [84], [217], [214], [112]	7, 40, 35, 18, 38	27, 10, 42, 13, 22
11	Article	[30], [13], [15], [169], [211],[144]	71, 36, 24, 15, 37, 15	35, 16, 27, 25, 19, 35
12	Article	[19], [108], [171], [195],[138], [64]	63, 27, 12, 23, 43, 15	16, 20, 19, 43, 33, 20
13	Article	[230], [224], [167], [158], [69]	27, 25, 36, 11, 29	41, 21, 11, 34, 18
14	Article	[92], [99], [211], [208], [106], [57]	6, 26, 37, 52, 31, 34	23, 21, 17, 12, 36, 14
15	Article	[179], [74], [221], [130], [60], [146]	26, 45, 30, 28, 23, 17	32, 22, 18, 21, 41, 21
3	Article	[186], [128], [164], [90], [156]	19, 71, 40, 37, 52	32, 42, 24, 12, 32
17	Article	[229], [119], [219], [187], 181]	45, 23, 42, 12, 42	11, 38, 17, 33, 25
18	Article	[148], [139], [226], [184], [192]	12, 23, 31, 54, 31	44, 59, 29, 38, 49
19	Article	[206], [105], [216], [137], [189]	35, 32, 31, 13, 24	15, 13, 61, 22, 53
20	Article	[23], [131], [219], [157], 214]	11, 31, 41, 21, 15	41, 23, 81, 31, 54
21	Article	[20], [190], [163], [182], [200]	7, 32, 25, 16, 17	18, 19, 32, 24, 51
22	Article	[111], [215], [173], 154], [170]	28, 41, 21, 16, 19	13, 29, 17, 38, 27
23	Article	[225], [91], [39], [28], [207]	31, 14, 16, 27, 11	61, 27, 45, 25, 22

24	Article	[204], [113], [126], [150],[41]	21, 12, 14, 17, 31	35, 28, 27, 33, 32
25	Article	[9], [50], [73], [134], [220], [191]	7, 9, 13, 3, 8, 16	52, 26, 41, 73, 17, 11
26	Article	[209], [115], [71], [16], [109]	54, 34, 26, 37, 28	40, 29, 23, 22, 19
27	Article	[43], [142], [145], 166], [222]	10, 9, 13, 21, 42	25, 37, 33, 29, 22
28	Article	[18], [54], [88], [129], 153]	26, 38, 16, 38, 37	48, 22, 39, 48, 39
29	Article	[31], [26], [209], 227], [89]	21, 4, 51, 32, 16	57, 43, 82, 23, 12
30	Article	[38], [53], [12], [107], [213]	11, 32, 25, 26, 14	14, 27, 45, 16, 45
31	Article	[205], [10], [36], [85], [66],	15, 73, 42, 61, 39	33, 26, 18, 12, 35
32	Article	[197], [193], [70], [45], [165],	16, 31, 52, 43, 13	11, 24, 19, 38, 12
33	Article	[155], [48], [55], [136], [114]	15, 26, 36 ,63, 32	11, 56, 23 ,28, 45
34	Article	[176], [149], [104], [97], [168]	42, 35, 24, 29, 19	12, 42, 11, 10, 38
35	Article	[162], [147], [143], [72], [32]	32, 27, 20, 12, 18	46, 14, 16, 36, 60
36	Article	[82], [101], [51], [175], [169]	21, 27, 31, 62, 31	64, 45, 27, 49, 25
37	Article	[102], [118], [140], [202], [196]	41,16, 14, 23, 42	37,48, 37, 28, 52
38	Article	[146], [124], [95], [8], [40], [29]	27, 21, 30, 25, 17	42, 33, 26, 39, 14
39	Article	[58], [[174], [160], [178], [151]	6, 17, 21, 13, 9	47, 22, 25, 48, 19
40	Article	[180], [100], [93], [59], [77]	21, 38, 32,14, 18	55, 37, 16,39, 20

III. HISTORY

Q1 What is the detailed history of DTs from origin to present?

The history of the concept and its progression throughout its existence is broken down into the following subsections. While focusing on the term "digital twin," I also include other synonyms and phenomena that coincide with the digital twin concept, at least partially. This inclusion is especially important when documenting the early origins of the concept.

Pre-2000: According to the most widely accepted academic and industrial consensus, Dr Michael Grieves was the first to introduce the digital twin concept in his presentation in 2002 [22]; however, this statement is not true. Because the concept which was taken from 2002 contained only real and virtual space and connection, as shown in figure 2. The concept was introduced only in the context of Product Lifecycle Management (PLM), then called the (conceptual ideal for PLM). Some scholarly articles have established a link between digital twins and Plato's "Allegory of the Cave." [23]–[25]. While these connections may not have any immediate impact, they show that the basic concept of mirroring the real world, as shown in figure 2, which is essential to the digital twin concept, has been around since Ancient Greece. Making digital twins is a natural human instinct, it would seem.

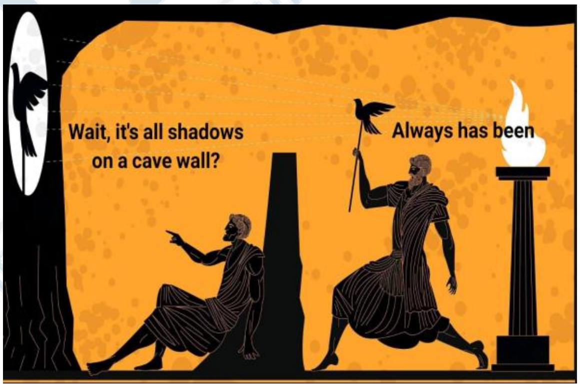

Figure 2. Shows the twinning shadow of the physical reality from the Allegory of the Cave [26].

Many people now consider the workshop on artificial intelligence (AI) held as part of the Dartmouth Summer Research Project in 1956 and was organised by John McCarthy to be the field's official declaration as a research field in AI [27]. Since 1956, AI research has produced intelligent systems that can make decisions, reason, predict the future, and perform physical tasks. The applications of AI are now an integral part of daily life due to the development of Machine Learning (ML), Deep Learning (DL), Central Processing Units (CPU), Graphics Processing Units (GPU), Tensor Processing Units (TPU), and computational power. Through the use of system engineering and condition monitoring in the year(1961-1972), NASA was the first organisation to conceptualise the idea of a "(physical) twin". As part of the Apollo 13 mission, two spaceships that were completely identical to one another were constructed;

however, only one of the spaceships was sent into space to complete the mission [20]. The other spaceship remained on earth, as shown in figure 3. NASA used the satellite that was allowed to return to earth to research events that occurred in space. They were aware of the phenomenon surrounding the digital twin technology and immediately began investigating the effects that the technology would have on business [28], [29].

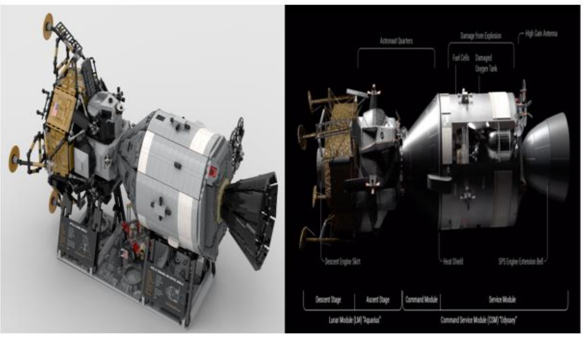

Figure 3. Shows the physical twin as part of the Apollo 13 mission

Sir Tim Berners-Lee made the first proposal for the World Wide Web (WWW) in 1989. He stated that each information node of the proposed system should "represent or describe one particular person or object's [30] Some examples include concepts, different types of hardware, and specific hardware objects. Even though, as is common knowledge, the World Wide Web has not yet been able to replicate real-world phenomena with the same degree of accuracy as they exist in the real world; rather, it provides pieces of information scattered across poorly organised pages. The book "Mirror Worlds" by David Gelernter in 1991 is where the first detailed conceptualisations of mirroring the real world with software appear to have been published [31]. Additionally, the same book was considered the initial concept by research done more recently on the digital twin [32], [33]. Solutions for the closely related paradigm "Internet of Things", which aims to close the gap between the physical and digital worlds, began to emerge in the latter part of the second millennium [34]–[36]. In 1998, Bruns referred to the virtual counterparts of his "integrated real and virtual prototyping" solution as "twin objects", another term that he coined [37]. Despite this, the idea of a digital twin had not been sufficiently formalised by the turn of the millennium. The evolution of the IoT, closing the gap between the physical and digital world[38]

2000-2010: The beginning of the new millennium marked the beginning of the commercialisation of research on the Internet of Things, which meant that an increasing number of individual physical objects from the real world started to have a digital presence. Several researchers primarily focused on computer science have recently begun using the term "virtual counterpart". Many different terms could be used to describe the phenomenon [33], such as product agent [39], product avatar [40], and holon [41].

Product lifecycle management (PLM), a methodology for managing the engineering data associated with a product, was being developed simultaneously [3]; in 2003, Grieves introduced DT in the framework of PLM, but the definition used to introduce them was ambiguous, and the notion was confusing even within the context of PLM. The term "digital twin" was first used in a conference paper in 2005 but has yet to be widely adopted [42]. Overall, the decade demonstrated academic development of the digital twin concept on various fronts in computer science, control engineering, and mechanical engineering.

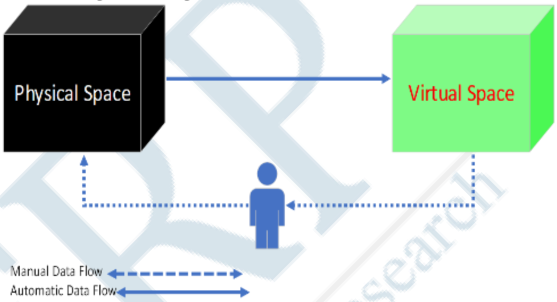

Figure 4. Shows the early concept of the DT

2010-2015: Rather than using a technical mirroring method, Puig and Duran's "Digital twins" conference paper emphasised the creation of recognisable human avatars. These human avatars illustrate that the phrase "digital twin" can have meanings outside of engineering circles [43]. NASA published a draught of its strategic roadmap in November 2010, defining the "digital twin" as a simulation-based system engineering approach. The digital twin is 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 many more to mirror its flying twin [44]. The newly defined digital twin paradigm created a buzz among aerospace researchers, including a general description of digital twin aspirations for NASA and the US Air Force and more targeted investigations on modelling and predicting structural life[45]–[47]. NASA and a few aerospace industry members [5] started to simulate different rockets and aeroplanes, respectively. Since then, DT has become a trendy topic; all industries began using other techniques and naming them DT. Because the actual concept and definition were not specified, academia brought further confusion and imprecision to the idea, modern procedures, obsolete technology, and even the present-day DT [48].

2015-Present: In 2015 the term "digital twin" was used significantly more frequently in academic publications. While concentrating on aircraft's implications, [49] reviewed the overall concept and compared the twin and avatar terms. [46] outlined the application of digital twins in manufacturing.

2016, several publications focused on general manufacturing and simulation helped break the academic use of the term "digital twin" free from its association with the aerospace industry. Boschert and Rosen described the digital twin concept as the next wave in simulation technology, which features assistance along the entire life cycle through linkage to operational data as an upgrade from simulation-based system design. In other words, the digital twin concept is an evolution of simulation-based system design [28]. [50]explored the visualisation of digital twins using web services and augmented reality, extending the concept beyond the scope of simulation. Canedo described digital twins as a solution to manage (industrial) IoT devices throughout their lifecycle by employing a graph-focused approach in which a subgraph of nodes represents real-world objects. This approach was developed in response to Canedo's identified problem [51]. What Canedo described is IoT devices' lifecycle can be managed using a graph-focused approach, where real-world objects are represented by nodes in a subgraph of the graph. [52]carried out an in-depth literature review for the digital twin concepts in manufacturing, covering several related terms. Research using other terms frequently resulted in the development of certain aspects of digital twins. For instance, data proxies were used to estimate the state of objects with minimal input data [53], [54].

IV. CONCEPTS AND DEFINITIONS

Q2 What are the DTs' definitions and concepts across academics and industries?

The literature demonstrates a variety of DTs conceptions and definitions; concepts differ by industry and even within each sector. Each application may provide a unique vision of the DTs. According to historical data and background information on the DTs, it was determined from the literature that the DTs notions may be classified:

4.1 Academic view on DTs' concepts and definitions

The US Air Force Research laboratory, University of California- Los Angeles, the University of Illinois at Urbana – Champaign University of South Carolina defined DTs as a highly accurate representation of the state of an aircraft as it was created and maintained, with particular reference to the materials and production requirements, controls, and method used to construct and maintain a specific airframe [55], [56]. The University of Cincinnati defined DTs as a digital representation of a real machine that functions in the cloud platform and replicates the health status using integrated knowledge from data-driven analytical algorithms and other available physical knowledge [57]. The Belarusian State University of informatics and Radio-electronics defined DTs as a digital replica of a real-world physical installation that can be used to verify the consistency of monitoring data, perform data mining to detect and forecast current and upcoming problems, and use artificial intelligence knowledge engine to assist in making sound business decisions [58]. Vanderbilt University GE Global Research Centre defined DTs as: "If the digital model follows the same load history as the actual aircraft wing, it can integrate various uncertainty sources over the entire life of the aircraft wing as well as heterogeneous information. It can also reduce the uncertainty in model parameters, track the time-dependent system states using measurement data, and predict the evolution of damage states if no measurement data is available [59]. The University of British Columbia, Lowa State University, Department of National Defence Canada defined DTs as real-time sensory data, a living model that can continuously adapt to environmental or operational changes. This living model can also predict the future of corresponding physical assets for predictive maintenance [60]. The Polytechnic University of Madrid and AIRBUS Group defined DTs as the creation of a digital counterpart to a product that exists throughout the product lifecycle, from conception to design to usage and servicing, and that is aware of the product's past, present and future states, as well as the facilitation of the development of product-related intelligent services [61]. Friedrich Alexander-Universitat Erlangen-Nurnberg, University Paris-sud defined DTs as a bidirectional relationship between a physical artefact and a collection of virtual models that efficiently execute product design manufacturing, servicing, and a variety of other activities throughout the product life cycle [62]. The Ruhr University of Bochum defined DTs as Having high semantic content and considering virtual product models and feedback data from the physical product throughout its lifecycle [63]. The Federal University of Rio Grande de Sul defined DTs as The product lifecycle represented by models from various product lifecycle stages. These models include system models, functional models, 3D geometric models, functional models, manufacturing models, and usage models, which constantly interact with one another [64]. Technische Universitat Berlin, Fraunhofer Institute Production Systems and Design defined DTs as virtual product and manufacturing process models that link enormous amounts of data to fast simulation, allowing for the early and efficient assessment of the consequences and performance and quality of design decisions on products and manufacturing lines [65]. Technology Guangdong, University of Technology defined DTs as the cyber layer of CPS, which evolves independently and integrates closely with the physical layer [66].

The University of Stuttgart defined DTs as a digital representation of a physical asset containing all its states and functions and collaborating with other DTs to achieve a holistic intelligence that allows for a decentralised self-control line [67]. Politecnico di Milano defined DTs as a virtual and computerised counterpart of a physical system that can benefit from real-time synchronisation of sensed data collected in the field and is closely linked to industry 4.0 [68]. The Chalmers University of Technology defined DTs as digital replicas of a product or production system used throughout the design, preproduction, production phases, and real-time optimisation [69]. Fraunhofer-Chalmers Centre for Industrial Mathematics, Reutlingen University, defined DTs as a digital replica of a product or production system that can be used throughout the design, preproduction, and production phases or real-time optimisation [70].

Beijing Institute of Technology defined DTs as a dynamic model in the virtual model that is entirely consistent with its corresponding physical entity in the real world and can accurately simulate the characteristics, behaviour, life, and performance of its physical counterpart promptly in the virtual model [69]. University of Applied Sciences of Southern Switzerland defined DTs as a digital avatar encompassing CPS data and intelligence, representing the associated CPS's structure, semantics, and behaviour and providing services to mesh the virtual and physical worlds [71]. The Pennsylvania State University, Indian Institute of Technology defined DTs as a In addition to providing a rigorous validation for the additive manufacturing process, predicting the most crucial variable that influences the metallurgical structure and properties of the components, and replacing extensive numerical experiments with rapid, low-cost numerical experiments are also being investigated [71].

4.2 Industrial view on DTs' concepts

Numerous organisations give different tools and software for DTs to visualise actual products and increase business through various industry sectors. The following firms are examples of the types of software they provide and describe data transformation.

Altair*;** They provide CAE tools, "A capability with which product performance predicted, optimised, tracked, and measured throughout the product life cycle" [72]. ***Amazon EC2*;** AWS provide a "cloud-based environment for cloud deployable web application" [73]. ***ANSYS*;** They provide CAE tools, "Combining all organisation's digital information on a specific product and merging physics-based understanding with analytics" [74]. ***Autodesk*;** They provide Reality capture technology and design software, "Spanning both the factory and product and making use of the augmented reality technologies borrowed from an IoT cloud services platform provider, has contributed capabilities to the company's media and entertainment software line." [75]. ***Bsquare*;** They provide Bsquare IoT, a "Digital representation of real-time configuration and state information of physical devices" [76]. ***Dassault*;** They offer a 3D experience platform, "A virtual equivalent to a physical product, which can improve manufacturing excellence by allowing people across the enterprise to collaborate and achieve continuous process improvement" [77]. ***Deloitte*;** They provide an IoT solution, "An evolving digital profile of the historical and current behaviour of physical object and process that helps optimise business performance" [78]. ***Docker*;** It is a product that uses operating system-level virtualisation to develop and deliver software in containers [79]. ***General Electric (GE); They provide Predix platform "providing software representation of a physical asset based on Predix platform and enable companies to understand better, predict, and optimise the performance of each unique asset" [80]. ***Infosys*;** They provide Infosys Nia TM platform, "Virtual replication of physical products, systems, and process that are indistinguishable from their real counterparts" [81]. ***Intellectsoft*;** They provide AR solution in construction, "A real-time digital representation of a physical object that continuously monitor changes in environment and reports back the updated state in the form of measurements and pictures [82]" . ***International Business Machines* (IBM);** They provide SAP Leonardo Platform, "A virtual representation of a physical object or system across its lifecycle, using real-time data to enable understanding learning, and reasoning [83]". ***Microsoft*;** They provide Azure IoT Hub Microsoft Hololens, "Visualising the physical world, being intelligent, collaborative, interactive, and immersive, and providing a method to simulate electronic, mechanical, and combined system outcomes [84]. ***Oracle*;** They provide Oracle IoT cloud, "An important concept that is going to be strategic to business operation as IoT deployments proliferate through the organisation [85]". ***PACCAR*;** They provide a Data V system, "A virtual version of an engine based on sensor data from the real-world versions to manage the maintenance and repair of engines [86]". ***Parametric Technology Corporation (PTC);*** They provide PTC Creo simulate and another analytics tool, "A digital depiction of a field-based object, encompassing its current and previous configuration states, considering serialised parts, software versions, options, and variants [87]". ***Siemens;*** They provide Siemens PLM software, "production of DT for manufacturing and production planning, and performance DT for performance, and acting on operational data [88]". ***Sight Machine*;** They provide a Sight Machine platform, "Offering sets of analytical models that mirror the entire production process, encompassing machines, lines, plants, or supply chains.". ***Simulating Critical infrastructures (SIM-CI);*** They provide DTs cities platform, "A digital copy of a city allowing us to mimic its vital infrastructures accurately [89]". ***System Application and Products (SAP);*** They provide the SAP Leonardo platform, an "Alive digital representation or software model of a connected physical object [90]". ***TIBCO;*** Software. They provide Project Flogo and TIBCO graph database, "A software representation of a device that can create efficiencies across the entire product lifecycle [91]". ***Twin Thread*;** They provide a Software solution, "A digital representation of any physical asset, including all the information about the asset's current and historical running conditions [92]"

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V. MISCONCEPTIONS

Q3 What are the misconceptions of the DTs?

5.1 Product avatar

The concept of the Product Avatar is rooted in efficient specific information management [93]; however, [94] highlights and emphasises that the notions of product avatar and product agent are utilised interchangeably. In 2013 Hibernik revisited his definition 2006 to introduce a new description of the product avatar [95] as a distributed approach to the interaction with and management of item-level product lifecycle information that has been developed for use in the manufacturing industry. Expressly, a digital counterpart or set of digital counterparts representing the attributes and services of a physical product to the various stakeholders involved in its lifecycle is understood to be included in the definition. Despite the different concepts of the product avatar, the work still focuses only on the product-service systems [96], [97].

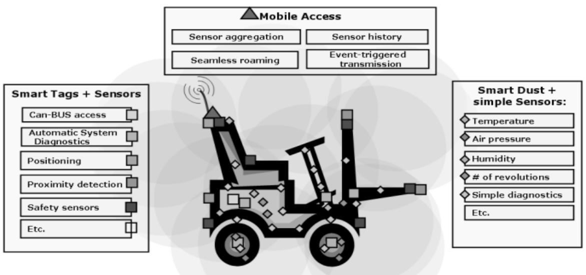

Figure 5. Shows the Smart Tags and Sensors for the Product Avatar Concept [98].

5.2 Cyber-physical equivalent (CPE)

The concept of CPE is not new; however, it should be considered in the context of CPS, which was defined in 2008 as the connection of computation with processes of the Physical Twin [99], where the embedded sensors and computers, along with the network, can monitor and control the physical processes [53, the CPE concept was. In 2015 the CPE concept was a newly emerging technology. It is defined as a virtual representation (a virtual replica) of a production system that is completely synchronised with the physical one in all aspects: geometry, function, and behaviour, as shown in figure 4.

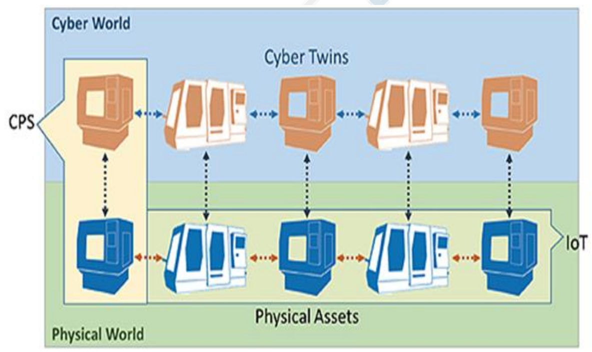

Figure 6. Shows cyber-physical equivalent structure

Because cyber-physical equivalence is defined by the networking and interaction of computing and Multiphysics systems, physical systems may be mechanical or electrical. Control systems, planning, or even signal processing could be considered computational—the interaction of these systems with their environments, humans, or each other results in CPSs. CPE and DTs are related concepts that are connected by sensors and networking. On the other hand, the DTs are limited to the digital model. Simultaneously, cyber-physical systems are defined by their DTs and physical assets, implying that the DTs serve as foundations for creating CPE [101].

5.3 Digital Model (DM)

A digital model is a digital representation of a physical thing that does not involve automated data exchange between the physical and digital objects; the two-way manual data flow characterises the digital model. A digital model can represent a physical object that exists or will exist in the future. There is a possibility that the digital representation will include a description of the actual object that is more or less exhaustive. These models may include simulation models of proposed factories, mathematical models of new products, or any other models of a physical thing that do not involve automatic data integration. The digital model focused on "what if," or what might happen in the real world. However, the DTs are much more than digital models because the DTs continuously monitor, control, and diagnose what is happening in real-time to predict and optimise situations and systems [102]. While digital models have a close definition or description to the DTs, there are significant distinctions between the two DTs having automatic data flow and digital models having manual data flow.

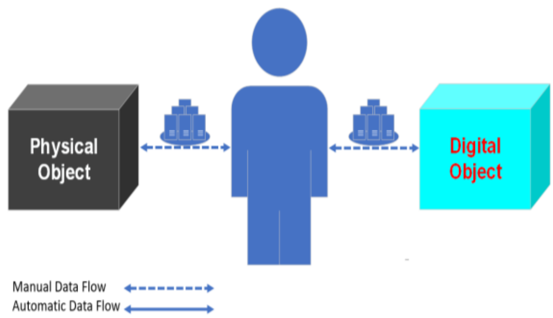

Figure 7. Shows the digital model process where all the data is transferred in two ways manually.

Nevertheless, this is not a comprehensive list of the models that fall under this category. Digital data of existing physical systems may still be used in constructing these models, but the data exchange will be manually handled the entire time. The status of the digital object is unaffected by any changes that occur to the state of the physical object and vice versa.

5.4 Digital Shadow (DS)

According to the concept of a Digital Model, if there is also an automated data flow in only one direction between the state of an actual physical object and a digital object, one may call the combination of these two things a Digital Shadow. A shift in the state of the physical object will cause a corresponding shift in the state of the digital object, but not the other way around. that the digital shadow can be defined as an image of an item that only moves in one direction between the physical and digital worlds. Instead of the reverse, a change in the physical object's state causes a change in the digital object. Nevertheless, the terms "DT", "Product Avatar", "Internet of Things", "Cyber-Physical Equivalence", and "simulation" still have distinctions between them despite the similarities and overlapping. Two similar systems, physical and computational, can be considered DTs—a more direct depiction of any physical system in computer form, referred to as a product avatar. CPE is defined as the relationship between interconnected computer systems and physical systems. Until the beginning of 2008, the product avatar dominated the manufacturing world. However, by the end of 2010, the literature indicated that engineering and manufacturing had adopted DTs as their domain.

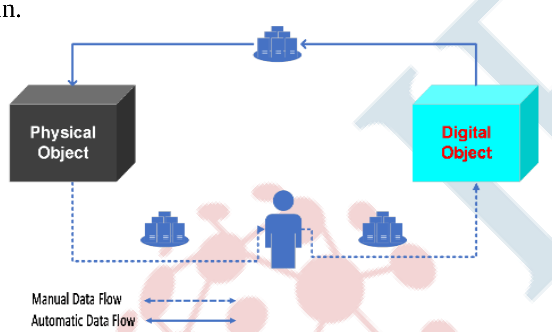

Figure 8. Shows the process of the digital shadow

VI. LEVELS

Q4 What are the levels of DTs?

6.1 Digital Twins (DTs)

In this paper, DT is defined as a" live digital replica that continuously simulates and connects the entire mechanical behaviour of anything", where data flows between an existing physical thing and a digital entity and are completely integrated into both directions. The digital item may also serve as the controlling instance of the physical object in such a combination. Other physical or digital items may cause the digital object to undergo state changes. A change in the physical object's state directly affects the digital object's state and vice versa

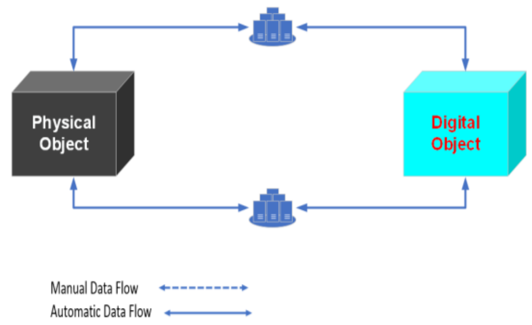

Figure 9. Shows the fully automated process of the DTs

According to the literature, the term "(digital) twin" was coined for the first time in 2002 by Michael Grieves in the context of PLM, and it was published in the journal Science (PLM). It had an informal definition when the DTs were first introduced [3], [42]. Greaves defined DT informally as a replica of the actual physical system under consideration. This replication has three dimensions, according to him: (A) a physical entity, (B) a digital counterpart, and (C) a connection between the physical and digital. Although this was not a formal definition, it was a good start. However, the informal description resulted in a significant breakthrough in the industries, but it also caused confusion and misunderstanding about the concept, which led to Grieves' resignation. In 2005, he revisited his 2002 definition and divided it into three categories, which he first presented in 2001 and revised in 2005 [3], (A) DT prototype, (B) DT aggregate, and (C) DT instance. A more transparent and explicit conceptualisation was presented [5].

6.2 DTs' Web

The term "Digital Twin Web" (DTW), sometimes known as "Twinweb", was defined as "an ongoing development effort for constructing a global network of digital twins in a similar internet-native and user-friendly manner as the World Wide Web (WWW) gives information to people." [104]. Readability for both humans and machines is a priority for Twinweb. The twins each describe their relationship with the other twins in the series, creating a knowledge network based on the real world. Twinweb relies on DTs' documents to provide descriptions of twins and requires some form of a standardised protocol to facilitate the transfer of these documents. Before utilising Twinweb effectively, it is necessary first to standardise the fundamental structure and the protocol. The author has developed Twinbase, server software for the Digital Twin Web that is open source. As seen in Figure 4.4, the primary objective of Twinbase is to facilitate the distribution of DT documents from owners to users.

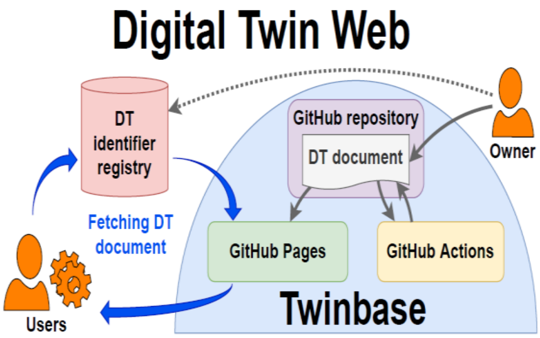

Figure 10. Twin base acting as a Digital Twin Web server [105]

6.3 DTs' web structure

It was necessary first to establish the fundamental framework of the Digital Twin Web before a Digital Twin Web server, such as Twinbase, could take its definitive shape. Figure 4.4 illustrates the structure, and digital twin papers can also be served from various Web server software that is part of the Digital Twin project. Nevertheless, the structure is now just a suggestion, which must be validated and changed by what works in practical development. The digital twin identifier (DTID) registries and DTW servers are what make up the Digital Twin Web (DTW) according to the structure that has been proposed for it by [105]. Users can retrieve a DT document by first querying a DTID registry for the document's location and then retrieving the document itself from the server after receiving the location from the registry. The owner of a digital twin is the only person who can change the digital twin's register record and the digital twin's associated document.

6.4 Hybrid Twins (HTs)

HT is an extension of the DT in which the isolated DTs models are interlaced to recognise, foresee, and communicate less optimum (but predictable) behaviour of the physical counterpart well before such behaviour occurs. The connection is made to maximise the overall system's efficiency. The HTs integrate data from various sources (such as sensors, databases, and simulations…) with the DTs models and apply AI analytics techniques to achieve higher predictive capabilities while simultaneously optimising, monitoring, and controlling the behaviour of the physical system. In other words, the HTs can do all these things to achieve synergy among the DTs models; the HTs are often manifested as a collection of all related models.

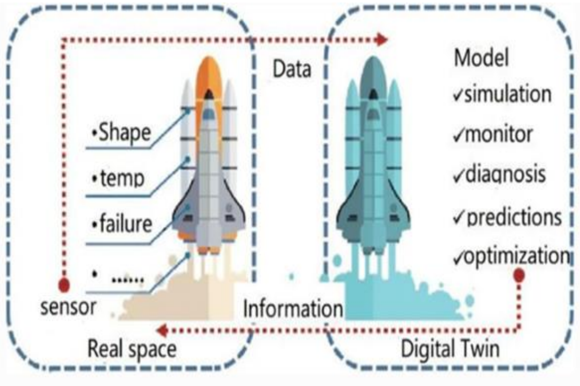

Figure 11. Shows the Hybrid Twin [106]

6.5 Cognitive Twins (CTs)

The term "CT" refers to an extension of "HT" that incorporates cognitive features that will enable sensing complex and unpredicted behaviour and reasoning about dynamic strategies for process optimisation. This cognition results in a system continuously evolving its digital structure and behaviour. CT is an extension of "HT". A CT is, in this sense, a hybrid, self-learning, and proactive system that will maximise its cognitive capacities over time based on the data it will gather and the experience it will gain throughout its existence. By integrating the knowledge of subject matter experts with the capabilities of HT, a CT can produce novel solutions to newly arising problems. Therefore, a CT will accomplish synergy between the HT and the expert and problem-solving expertise it possesses.

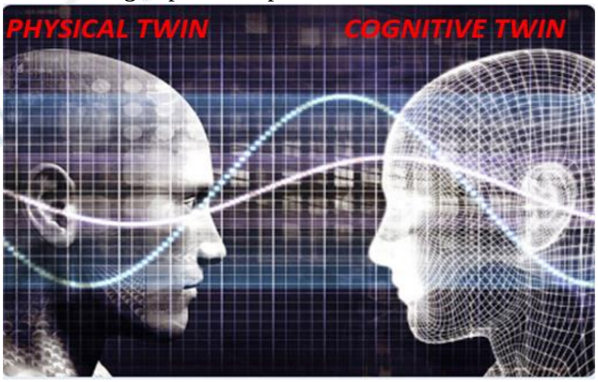

Figure 12. Shows the CogniTwin where the CogniTwin behaves exactly like the physical.

6.6 Physical Twins (PT)

NASA first introduced the concept of the Physical Twin in the aerospace industry during the Apollo programme, when two identical space shuttles were built to use one in space. A second person will be on the planet to study the shuttle's behaviour in the area and to keep track of its conditions through the shuttle's presence on it [2], [5].

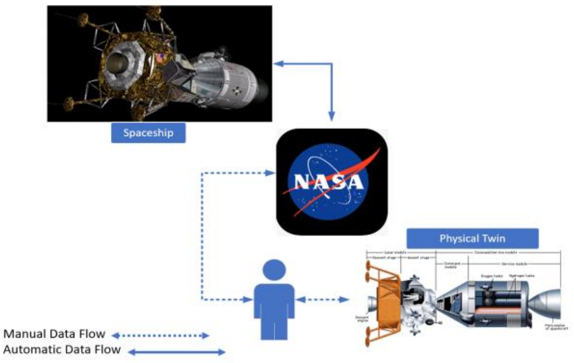

Figure 13. Shows NASA's first introduced the concept of the Physical Twin

VII. APPLICATIONS

Q5 What are the applications of DTs?

In the following part of our examination, we will focus on the many different applications of digital twins. The first thing that we are going to do is investigate the several ways in which digital twins could be utilised in the future. We will discuss the industry, the domain, and the specific challenges that digital twin technology must overcome. The concept of a digital twin and the expression "digital twin" is currently gaining popularity among academics everywhere. The advancements that have been made in the field of artificial intelligence (AI) and the internet of things (IoT) are making it possible for this expansion to accelerate [107]–[112]. Currently, the primary areas of concentration are smart cities and manufacturing, with some uses of Digital Twin technology identified as related to the healthcare industry.

7.1 Manufacturing

DTs technology is currently being tested and evaluated for its next potential application in manufacturing. The fact that manufacturers are always looking for new ways in which their products can be tracked and monitored to minimise costs and save time is the primary cause of this phenomenon. This live monitoring is the key motivator and driving force behind any manufacturing process. It would appear that digital twins are having the most significant impact inside this context due to this fact. Analogous to this, constructing a smart city is one of the key motivating drivers for utilising digital twins in the manufacturing industry. Connectivity is an essential part of this, which takes advantage of the connection of various devices in order to make the idea of a "digital twin" a reality for the processes involved in production [113]–[117]. DTs can provide real-time feedback on the operation of production lines as well as information regarding the performance of machines. Additionally, DTs can provide these statistics in an easily digestible format. It allows the creator to foresee potential issues at an early stage. The utilisation of digital twins encourages connectivity and feedback between devices, which ultimately results in gains in terms of both performance and reliability. AI algorithms associated with DTs can attain a higher level of accuracy since the machine can store enormous volumes of data, which is essential for performance and prediction analysis. Establishing an environment to test products and a system that acts on real-time data by DTs can be an exceptionally valuable asset within a manufacturing environment [118]–[121].

Numerous manufacturing-related works use the DTs to optimise every step of the product- and process-manufacturing process. Among these, [122] emphasise how using DTs may enable the establishment of a computerised system that oversees each manufacturing stage using a modular approach. More specifically, [123] presents a modular approach to smart manufacturing, where autonomous modules conduct high-level activities without human control, choose from a variety of alternative actions, and react to failures or unexpected events without interfering with the operation of other modules (thus avoiding changes and reconfigurations at the supervisory level). However, The modules must have access to realistic data outlining the state of the process and the goods. These tasks and achievements can be accomplished by employing a DT, a faithful virtual representation of the actual physical entities. DTs enable ongoing communication between the system and the physical asset in the example. The work of [122] shows its potential in the manufacturing industry. The DTs appear to be a realistic model or simulation capable of constant communication with its actual twin, which is an overly simplified way of explaining it [122]. DTs should not be confused with simulations or avatars generated by virtual/augmented reality applications [124]. As stated previously, artificial intelligence and continuous (or at least periodic) real-time data interchange between the physical model and its virtual counterpart distinguishes a simulated model or (Product) Avatar from a DT.

7.2 Aviation

While DTs technology is valued in manufacturing for enabling predictive maintenance and optimising and speeding up production, it is primarily used in aviation for predictive maintenance [125] - for example, to detect dangerous changes in structural aircraft and trigger self-healing mechanisms - decision support, optimisation, and diagnostics. The DTs model that best reflects the multi-physics, fluid-thermal-structural you-piling suitable to hypersonic flow circumstances of aircraft may be chosen by specifying a quality measure as a decision-making metric for autonomous model fidelity selection [126]. [127]described an aircraft DTs for studying crack tip deformation and propagation in aluminium alloy and steel utilising automatic picture tracking. Throughout the whole aircraft lifecycle, the DTs models can predict sub-cycle fatigue fracture growth mechanisms of aviation materials, lowering development and maintenance costs [128]. DTs was developed by [129]to model how the performance of composites is impacted by microstructural changes brought about by multi-physical environments (such as electrical fields). [130]suggested DTs for detecting fatigue cracks using a shape memory alloy particle-filled finite element model of an aviation wing. The authors studied the response of localised particles to an aircraft wing subjected to flying stresses to detect structural changes. In order to identify and forecast damaged aircraft structures, the study proposed in [131]employed the Finite Element Alternating Method (FEAM) to compute the Stress Intensity Factor [132] and an improved Moving Least Squares (MLS) law to compute fatigue crack growth rates [133]. [134]describes a DTs that regulates aeroplane wings using a modified dynamic Bayesian network. Based on a related concept, [135]developed a computational steering framework for fatigue-damage prediction in full-scale laminated composite structures and tested it on wind turbine blades. It combined fatigue damage modelling, isogeometric analysis of thin-shell structures, and structural health monitoring. Modern aircraft DTs evaluate guided-wave responses to foresee damage [136] instantly. As the directed wave collides with harm, it weakens and reflects. Signal strength and phase changes differ between damaged and unharmed structures. During damage identification and evaluation, a genetic algorithm is used to properly quantify damage size, position, and orientation [137]. An aeroplane tyre at touchdown was built as DTs models by Zakrajsek and Mall [138].

7.3 Healthcare

DTs are initially used in healthcare for predictive maintenance and medical device performance enhancement (in examination speed and energy consumption). DTs also improve the lifetime of hospitals. The DTs from GE Healthcare improve hospital management. This international corporation's predictive analytics technologies and AI solutions convert medical data into actionable intelligence. The goal is for hospitals and government organisations to manage and coordinate patient care operations. To improve decision-making at Johns Hopkins Hospital in Baltimore, GE Healthcare created a "Capacity Command Center" [139]. The hospital improves service, safety, experience, and volume by establishing a DT of patient pathways that forecasts patient activity and plans capacity based on demand. Siemens Healthineers created DTs to optimise the Mater Private Hospitals (MPH) in Dublin [140], which was experiencing increased patient demand, increasing clinical complexity, ageing infrastructure, a lack of space, increased waiting times, interruptions, delays, and rapid advances in medical technology, which necessitated the purchase of additional equipment. MPH and Siemens Healthineers redesigned the radiology department using an AI computer model. Medical DTs enable digital process optimisation by simulating workflows and assessing unique operational situations and architectures. The DTs' realistic 3D simulations and descriptive and quantitative reporting allow for the prediction of operational scenarios and the analysis of various options for transforming care delivery. AnyBody Modeling System (AMS) (see https://www.anybodytech.com) shows how the human body interacts with the environment and was created due to a study into VPH. Muscle forces, joint contact forces and moments, metabolism, tendon elasticity, and antagonistic muscle activity can all be calculated using AnyBody. A DT-virtualized physiological model could predict organ behaviour. Automated CAD analysis may assess the efficacy of individualised therapies, advancing precision medicine. Picture Archiving and Communication Systems (PACS) [141], which provide affordable storage, quick access, and interchange of medical examinations (mainly images) from different modalities, are crucial in this field. Some organs DTs have been used in clinical practice as a reliable tool for experts, while others are being validated. The Living Heart [142]was built by Dassault Systèmes and introduced in 2015 (May). First DTs of an organ to consider blood flow, mechanics, and electrical impulses. The software converts a 2D scan into an accurate 3D organ model. The preliminary results of the experimental testing were promising. The human respiratory system is another organ DTs produced by Oklahoma State University's CBBL [143]–[146].

7.4 Smart Cities

DTs are gaining popularity as a result of the tremendous developments in connectivity made possible by the Internet of Things. They have the potential to be immensely useful in smart cities and are currently being employed in growing numbers. The use of DTs is expected to increase due to the growth of smart cities, which will result in greater connectivity among communities. Additionally, as we collect more data from the Internet of Things sensors that have been integrated into our major municipal services, it will open the door for research focused on developing powerful artificial intelligence algorithms [147]–[149]. The level of capability possessed by the infrastructure and services of a smart city. Having sensors installed throughout a city and monitoring it with internet-connected gadgets are two of the many approaches to preparing a city for the future. It can be put to use in a variety of ways to support the ongoing creation of additional smart cities as well as the planning and development of the smart cities that already exist. There are benefits associated with planning, but there are also benefits associated with energy conservation. These facts explain excellent comprehension of the procedures used to manage the circulation and consumption of our utility services. The idea of utilising technology that creates DTs are a step in the right direction for creating smart cities. It can create a living testbed within a virtual twin, which can accomplish two things: first, it can test different scenarios, and second, it can enable DTs to learn from their surroundings by analysing changes in the data they collect. This learning is accomplished through its ability to create a living testbed within a virtual twin. This capability can promote growth by making the process easier to complete. Both data analysis and monitoring are examples of potential applications for the information acquired. More opportunities for connectivity and more data can be used as more smart cities are developed [150]–[153]. The idea of DTswill become increasingly realisable due to this.

7.5 Maintenance

Because maintenance is the key to extending the lifespan of anything, it is also the fundamental component of safety. When determining when and how maintenance actions need to be carried out, one option is to use maintenance strategies as a guide. Types of Maintenance; Reactive maintenance, Preventive maintenance, Condition-based maintenance, Predictive maintenance, and Prescriptive maintenance

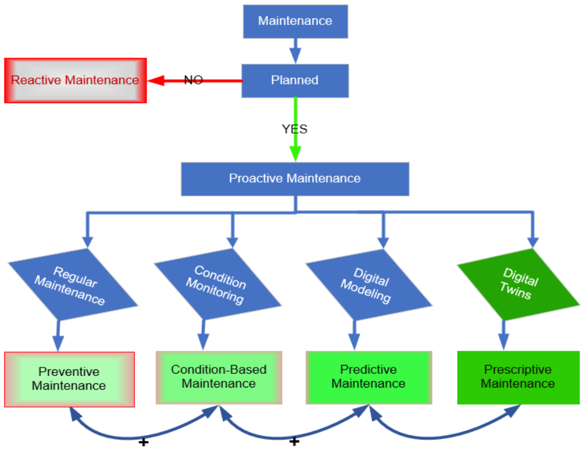

Figure 14. Shows the maintenance process to get to the DTs used in maintenance

Reactive maintenance; The first technique is called corrective or failure-based maintenance, and it is called reactive maintenance. It pertains to any serious situation considered an emergency, and a malfunction or breakdown has brought that on. These events were not included in any prior planning considerations [154]. ***Preventive maintenance;*** This strategy is based on the knowledge of the plant/infrastructure/asset manager, who schedules various maintenance tasks at various intervals over time to prevent service interruptions or, if necessary, reduce their impact by scheduling them in advance. Even though this level is significantly better than the reactive, it is still far from ideal: In this kind of plan, the trend is to over-maintaining the asset, resulting in a high economic cost [155]. ***Condition-based maintenance;*** Condition-based maintenance (CBM) anticipates asset maintenance based on indications of deterioration and deviation from the asset's usual behaviour. CBM is also referred to as diagnosis-based maintenance. The maturation of technologies such as IoT and cloud computing, which are used to monitor the asset's condition, enables the detection of these anomalies. Condition-based techniques can be augmented by diagnostic and status data acquisition algorithms based on artificial intelligence [156]. ***Predictive maintenance;*** Various methods can be utilised to combine all relevant data for making maintenance predictions with maximum precision. An algorithm for analysing data is constructed based on the data at hand. It yields information on the trends before the asset's behaviour [157], [158]. [159] claimed that Predictive Maintenance was one of the most computationally-intensively researched issues in the current wave of Industry 4.0 research. ***Prescriptive maintenance;*** The final strategy is knowledge-based maintenance, often known as prescriptive maintenance. It alludes to planning maintenance better using forecasts. It is committed to prescribing an action plan in addition to employing historical and real-time data analysis to forecast the status of a necessary asset [160], [161].

Table 3. Shows the distribution of DTs applications vs top countries using DTs

Company	Ref	Description	Application
Aurus (Russia)	[162]	DTs were used to carry out virtual prototyping and verification to mimic the model of a physical product that may be represented, analysed, and tested as a real machine. The luxury car's production cycle was shortened from 5 to 7 years to just two years, four months.	Automotive, manufacturing, and maintenance. (reduced the production time from five or seven years to only two years after using DTs
Maserati (Italy)	[163]	created the DTs models for the car's development using the Siemens PLM software. Vehicle development time can be slashed by 30% thanks to virtual modelling and simulation that eliminates the need for costly, real-world prototypes, wind tunnel tests, and test drives.	Design, Automotive, and manufacturing. They reduced the cost of production by 30 per cent after using DTs
Tesla, Boeing, SpaceX (USA)	[164]–[166]	Every vehicle constructed would have DTs models that would link it to the factory and allow simultaneous data transmissions. The information gathered from the drivers enables better software and resource allocation for their vehicles.	Design, Production, Automotive, Aerospace, Manufacturing, and Healthcare. They had a big cut in the cost and the time is taken for production

Airbus (France)	[167]	built a data lake to serve as a repository for all currently operating aircraft. The A350 XWB aircraft instals 50,000 onboard sensors for each trip, generating 250 gigabytes of data. The data repository can be used to examine the components' lifespan performance and to gather information to enhance upcoming designs	Design, Automotive, Maintenance, and manufacturing. They reduced the cost of production by 30 per cent after using DTs
Rolls Royce (UK)	[168]	The engineering team simulates the functionality and condition of the actual machines using a digital twin. Scaled-down computer reproductions of actual engines are used to emulate the rigorous testing necessary for engine certification.	Automotive, manufacturing, and maintenance.
Schunk, Kompressoren (Germany)	[169], [170]	The whole engineering process—from the initial design to the mechanical, electrical, and software systems—has been digitalized. To help with product development, they employ DTs.	Design, Production, Automotive, Aerospace, Manufacturing, and Healthcare. They had a big cut in the cost and the time is taken for production
Philips (Netherlands)	[171]	They assisted their design progress by developing a digital twin of their medical equipment, which could be used in hospitals or for personal health gadgets	Automotive, manufacturing, and maintenance.

VIII. DEVELOPMENT

Q6 What are the enabling technologies for DTs?

8.1 Internet of Things (IoT)

The "Internet of Things" is a collective term used to refer to all the many devices connected to the internet. It is about giving so-called 'things' the ability to think for themselves and gather information about the environment in which they find themselves via artificial intelligence. When Kevin Ashton developed his plan for the Internet of Things in the late 1990s, the term "Internet of Things" was first used in a publication [172]. In this hypothetical situation, a programme would connect a Coca-Cola vending machine to the internet to check whether the beverage had adequately cooled down and was in a state where it could be purchased and enjoyed by a customer [173]. Due to the numerous sensors available today, the IoT concept is critical for its implementation. While the DT are a vision of the future fully connected world, they cannot exist in their entirety without sensors or a fully connected future vision based on the internet of things. An extensive benefit delivered by the advancement of the IoT brings the DT closer to realising its full potential. The IoT can be defined as the infrastructure in the physical space used to connect physical assets; thus, the internet of things utilises networking and sensors, whereas DT technologies utilise networking and sensors; however, the DT utilises the digital model in cyberspace[174]. The number of Internet of Things devices registered yearly demonstrates this technology's exponential growth. More than 17 billion people existed in the year 2018 [175]. By 2025, more than 75 billion devices will be operating, and [176] predicts that the market will be valued at more than $5 trillion. Many linked gadgets help to make the dream of a completely connected world a reality. All elements of daily life, including the communication business, the healthcare industry, the building and transportation industries, smart cities, and manufacturing, are impacted favourably by the growth of the Internet of Things devices [177], [178].

8.2 Data Analytics

Data analytics is a catch-all word that combines several different analytic principles found in various publications and academic settings. Consequently, an understanding of the prior publications and investigating them are essential. This subject area encompasses a large variety of subtopics. An inquiry into the data analytics industry is presented in the next part, focusing on providing additional detail. It will be helpful to the examination of other papers and the decision of where our research fits in if we first identify and then elaborate on these subject areas [179].

Data; Data cleaning is the last and possibly most significant step in the process. Even though the data has been gathered and organised, it is still possible that there are significant inaccuracies or missing data. During this cleansing stage, imputation procedures—previously recognised as challenges in data analytics—are used. These approaches ensure that the data is complete [180], [181]. ***Statistics;*** Data analytics utilises several methods, statistical inference and descriptive statistics, to characterise the observations based on the previously obtained data. AI and the problems stated below as examples of the expansion of advanced data analytics are shown below [180], [182]. ***Artificial intelligence;*** People's primary concern in data analytics is artificial intelligence (AI), which is becoming an increasingly important topic. It is generally agreed that the concept that "intelligent systems" ought to be constructed in the late 50s marks the beginning of the present conception of artificial intelligence [183]. These constructions are then categorised into topics that might be significant for this research, and a list of such issues can be found below [184], [185].

IX. CHALLENGES

Q8 What are the research issues of the DTs technologies?

Cost of Creation: DTs require rethinking software, production machine hardware, and cloud/physical interconnection. Only large corporations with enough money and employees can spread DTs technology. Several experimental DTs have been published or offered as research repositories in industry and medicine. Without open repositories, oligopolies may build and adopt DTs. Most companies can't build digital test twins with an army of engineers. Researchers and small enterprises could create modules for a single cloud platform and modular organisation. ***Architecture Pattern:*** There are two system architecture patterns: server-based and edge-based. In a server-based architecture, the data collected from a physical device is routed to a centralised server, performing data analysis and the construction of DTs for the device. This design pattern offers economies of scale while also facilitating simple maintenance. Data analysis is performed in an edge-based architecture rather than in the centre. As a result, data pre-processing is carried out locally and on the raw data captured from a hardware device. Consequently, if the edge-based architecture is designed correctly, it should be more effective at low-latency data processing. On the other hand, this pattern is more difficult. ***Communication Latency:*** The application determines the requirement for latency. The communication latency required between a physical device and its DTs is determined by the application scenario in which it is used. The latency is caused by the costs and difficulties associated with system development increase significantly as the communication latency requirement becomes more stringent to cover. As a result, shop floor monitoring based on DTs can tolerate higher latency than cloud-based industrial control in practice. BMW [85] specifies the nominal communication latency for various manufacturing applications, which is used as a guideline for designing the system architecture of DTs applications.

Data Capture Mechanism*:* Two standard methods are used to collect data from physical devices: capturing changes and taking snapshots. Capturing changes is the more common method. There is extensive use of both methods in large-scale computer systems, and sometimes a system will use the two methods. Validation is required for both approaches in specific application cases. ***Standards*****:** Although anyone can develop a DTs solution using standard technologies, standards will make it more likely that a DTs solution will last for an extended period. DTs solutions that are standard-compatible can benefit from the flexibility, interoperability, and scalability provided by existing and emerging standards for information models and communication protocols. When DTs are deployed in an open network of DTs, the used protocols are critical. ISO is actively developing a dedicated standard for DTs manufacturing [9]. ***Functionalities:*** Existing DTs applications are primarily designed for monitoring and prediction purposes and are also used as decision-support applications for humans in decision-making situations. Direct/autonomous feedback control from the DTs to the physical world is necessary, even though human involvement in the intelligent manufacturing environment is required. As a result, the DTs application has the potential to provide physical objects with a certain degree of independence. ***Models Management:*** DTs models can evolve due to engineering changes to their physical counterparts, changes in the modelling interests of the modellers throughout the physical image's lifecycle, and various other factors. The various versions of DTs models should be captured, stored, and integrated into these cases throughout the project's duration. The principles of snapshot-based and change-based version management are used to manage the various versions of DTs models efficiently and effectively. ***Security And Privacy:*** Any DTs environment must be created with particular attention to resilience concerning hacking and viruses because of the internet of things (IoT) and cloud computing. The theft of private, secret, or otherwise important information could cause damage to all of the sources participating in the twinned physical environment. Particularly for digital technologies used in the medical and healthcare fields, thorough consideration should be given to security and privacy issues.

X. FUTURE WORK

Q9 What are the directions for future research?

10.1 Technical Aspect

Improving Real-Time Simulation With DTs: The real-time simulation that is more accurate allows engineers and operators to visualise the dynamic behaviour of systems better while the systems are in operation. This simulation, in turn, allows operators to predict failure and avoid unnecessary downtime. [174], [186], [187]. Potential research questions might be***;*** Q1- How might standardised information architectures and models for DTs concept in simulation look like?***;*** Q2- What is the acceptable communication and interaction with DTs concept?**.** *Modelling Consistency And Accuracy:* Knowledge reuse and increased interoperability of production systems are made possible by modelling consistency in production systems. As a result of improved model accuracy, DTs functionality is enhanced, resulting in more consistent decision-making outcomes. [10], [188]. Accordingly, the potential research questions might be; Q1- What are the specifics of the DTs concept for different products and industries? Q2- What is the relevant information for internal and external stakeholders?

10.2 Business Aspect

Integrating Big Data Analytics into The DTs: DTs' exposure to a broader range of valuable data will increase, as will the ability to optimise and forecast effectiveness due to incorporating Big Data analytics. [30], [56], [57]; they highlight the necessity of stable solutions to handle large data. Accordingly, the potential research question may be; Q1- Which role do advanced analytic techniques play, and solutions for data security and privacy challenges; Q2- What is the role of the human in DTs concepts

XI. CONCLUSION

Although the study in this review was carried out in line with [12], the study has many restrictions. Despite this, it is impossible to ensure complete coverage of all aspects of DTs technology, primarily due to the many different concepts developed in academia and industry. On the other hand, the review ensures no ambiguity in understanding and that decisions are transparent. The guarantee of the study took place along the study in line with [11]. This systematic review is organised around ten research questions and is structured around DTs technologies in industries and academic settings. Specifically, the study presented comprehensive concepts in response to RQ1, followed by a review of state of the art in response to (RQ2), a discussion of research issues in response to (RQ3), classifications, and new directions for future research in response to (RQ4) (RQ4). Given that this review was initiated with fragmented work, there was no comprehensive perspective. Therefore, the contribution of the evaluation is rich in information for both academia and industry.

This review improved and enhanced the transparency for understanding DTs concepts and highlighted the benefits of DTs in various applications. This review benefits the industry and academia by providing new avenues for future research and suggestions for improvements and enhancements. This review Provided a comprehensive systematic analysis of the DTs' technologies; for the first time, using a systematic review methodology while incorporating the science mapping method. This review deeply examined DTs' concept, maturity, creation, values, applications, techniques, and technology and created the most suitable way to implement DTs in academia and industry through 230 publications. This paper sets out to guide the status of DTs development and application in today's academic and industrial environment. This review also outlined the current challenges and possible future work directions. This review consolidated the different types of DTs and definitions throughout the literature to easily identify DTs from the rest of the favourable terms such as 'product avatar', 'digital thread', 'digital model', and 'digital shadow'. This paper proposed a generalised concept/definition that encompasses the breadth of options available and provides a detailed characterisation which includes criteria to distinguish the Digital Twin from other digital technologies. The proposed concept/definition is "*Digital Twins are a live virtual replica that continuously simulates the entire mechanical behaviour of anything*".

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