DIGITAL TWINS:
A SURVEY ON ENABLING TECHNOLOGIES, CHALLENGES, TRENDS AND FUTURE PROSPECTS

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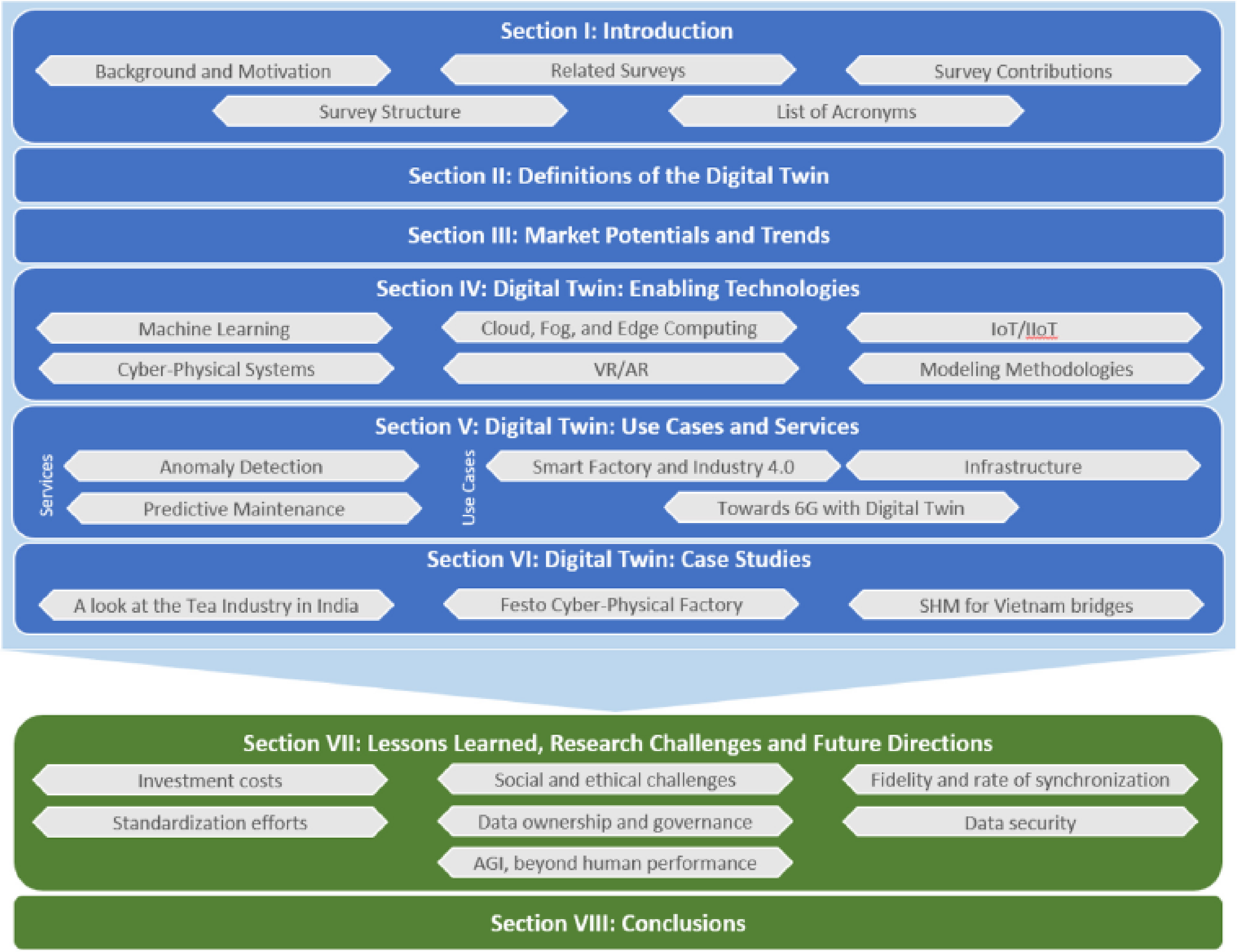
OUTLINE

ABSTRACT

- Digital Twin (DT) is an **emerging technology** that is a replication of all the elements, processes, dynamics, and firmware of a physical system into a digital counterpart.
- It is **enabled** by the Internet of Things (IoT), Artificial Intelligence (AI), 3D models, next generation mobile communications, Augmented Reality (AR), Virtual Reality (VR), distributed computing, Transfer Learning (TL), and electronic sensors.
- However, the development of this technology faces **many challenges**, such as complexities in effective communication and data accumulation, data unavailability to train Machine Learning (ML) models, lack of processing power to support high fidelity twins, and the absence of standardized development methodologies and validation measures.
- This survey paper aims to cover the important aspects in realization of the technology, including **design goals** and **objectives, design challenges** and **limitations** across industries, research and commercial developments, applications and **use cases**, case studies in industry, infrastructure and healthcare, and main service providers and stakeholders.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INTRODUCTION

- The **Covid-19 pandemic** has accelerated the digital transformation by several years, forcing industry executives to shift their focus from saving costs to increasing investments in digital development.
- **Cisco's 2020 Internet report** predicted a significant growth in Internet users, networked devices, and communication latency, leading to increased information dissemination, availability, and accessibility, as well as growing opportunities for development and innovation.
- **Industry 4.0 (I4.0) aims to automate** traditional, bare-metal industrial practices by bringing as much of the equipment from the physical space into the virtual domain.
- **Digital Twins (DTs) emerged** as an **experimental technology** set to enable replication of elements, functions, operations and dynamics of physical systems into digital world.
- **Recent developments** in Machine Learning, Artificial Intelligence, data integration Virtual/Augmented Reality, sensing, security, cloud storage, Transfer Learning, data visualization and ultra-reliable low latency communications (uRLLC) have enabled the implementation of the DT and its extended applications across several industries.

INTRODUCTION : CONTINUE – 1

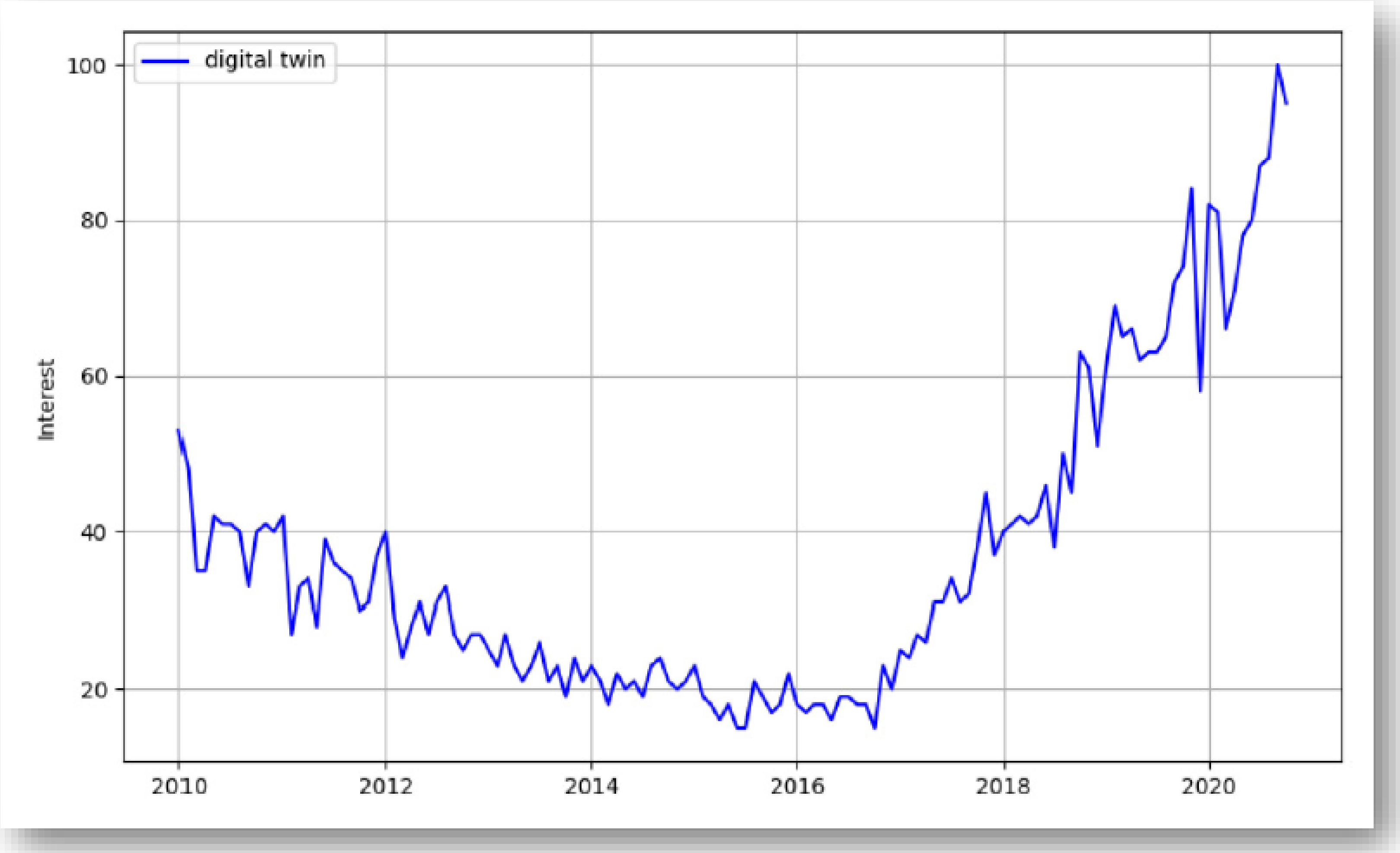
INTRODUCTION : CONTINUE – 2

- DTs enable **seamless data transfer** between physical and digital systems, allowing optimized learning, information transfer, analysis, visualization, optimization and planning to be used to **assess**, **observe** and **validate** the physical system, suggest changes and visualize potential improvements.
- This survey paper examines the **DT paradigm**, its market potential and trends, its most prominent enabling technologies, and its applications, frameworks, and case-studies.

BACKGROUND AND MOTIVATION

- Michael Grieves proposed the Digital Twin concept in 2002, which consisted of three main components: the **real space**, **virtual space**, and **link serving as a communication medium** between these two spaces.
- The most important idea of the DT concept is the conjoined **lifetimes** of the real and virtual entities, starting from the creation of the pair and ending in their disposal. This feature allows remote monitoring throughout the whole lifetime of the physical object, allowing it to be applied to other economic domains.
- The Figure (see Next Slide) shows the global trend of interest in the term "digital twin" as expressed by the normalized number of Google searches over the last 11 years.
- The "interest" shown on the Y-axis takes values between 0 and 100, where a value of 100 denotes the highest popularity and a value of 50 represents half of that maximum popularity. The last few years have seen increased attention to the concept, leading to increased research output and representation of the digital twin.

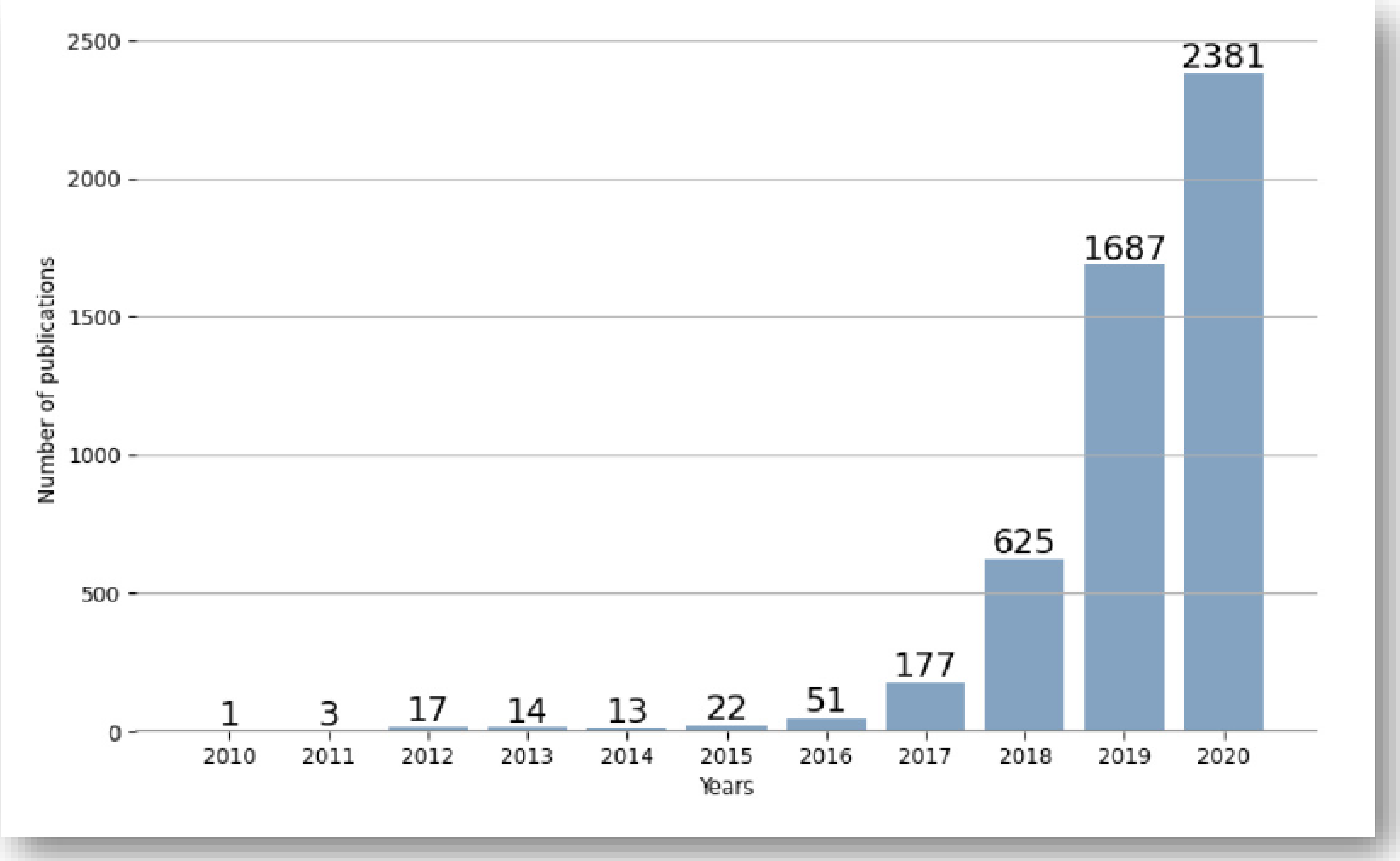
BACKGROUND AND MOTIVATION



BACKGROUND AND MOTIVATION: CONTINUE – 1

- The Google Search trend is a representation of the increasing popularity of the Digital Twin (DT) paradigm, which has been reflected in **research output**.
- The Figure (see Next Slide) shows the **number of publications** within the Scopus document database that included the phrase "digital twin" in their abstracts for each year in the last decade.
- The search was accomplished using the Python "pybliometrics" package.

BACKGROUND AND MOTIVATION: CONTINUE – 2



RELATED SURVEYS

- This work aims to provide a complete understanding of the concept of a Digital Transformation (DT) and its definitions, enabling technologies, applications, and use-cases and case-studies. It will review the **state-of-the-art** in DT development, illuminate fellow innovators on possible research gaps, questions and directions, and guide the industry towards possible DT use cases.
- Table I(see Next Slide) compares a collection of other survey articles and the survey paper to highlight the novelty of the work.
- **Barricelli et al [6]**. propose a study on the DT's **definitions, characteristics, applications**, and **design implications**. The paper provides full coverage of the DT's evolution, from Michael Grieves' concept to the state-of-the-art at the time of its publishing. The authors detail several DT implementations across three different application domains: **manufacturing, healthcare, and aviation**.
- They also discuss the market potential of the DT, the technologies that enable its characteristics, and possible use-cases in different industry domains. The paper ends with the design implications and challenges that developers should take into account when considering such a system.

RELATED SURVEYS: CONTINUE – 1

- ☐ **Minerva et al [7].** proposed a comprehensive survey on the **architectural models** of a Digital Transformation (DT) concept. The paper surveyed different DT characteristics that were highlighted in literature, such as **manufacturing, AR/VR, multi agent systems, virtualization, and IoT**.
- ☐ It also highlighted other important characteristics of the DT, such as data **ownership, contextualization, augmentation, servitisation**, etc. The paper covers the value of the DT concept, including its market potential, before diving into various detailed use-cases. The survey ends with a consolidated DT architectural model and illuminates the upcoming challenges.
- ☐ **Löcklin et al. [8]** published a survey paper that defines the Digital Twin (DT) as a tool for monitoring, **verification** and **validation**. The survey focuses on three research questions: **how the DT can enable verification and validation, the industrial domains where the DT is used for V&V**, and a **classification of modalities in which the DT is leveraged**. The survey is dedicated to studying the application of verification and validation within multiple industrial domains.

RELATED SURVEYS: CONTINUE – 2

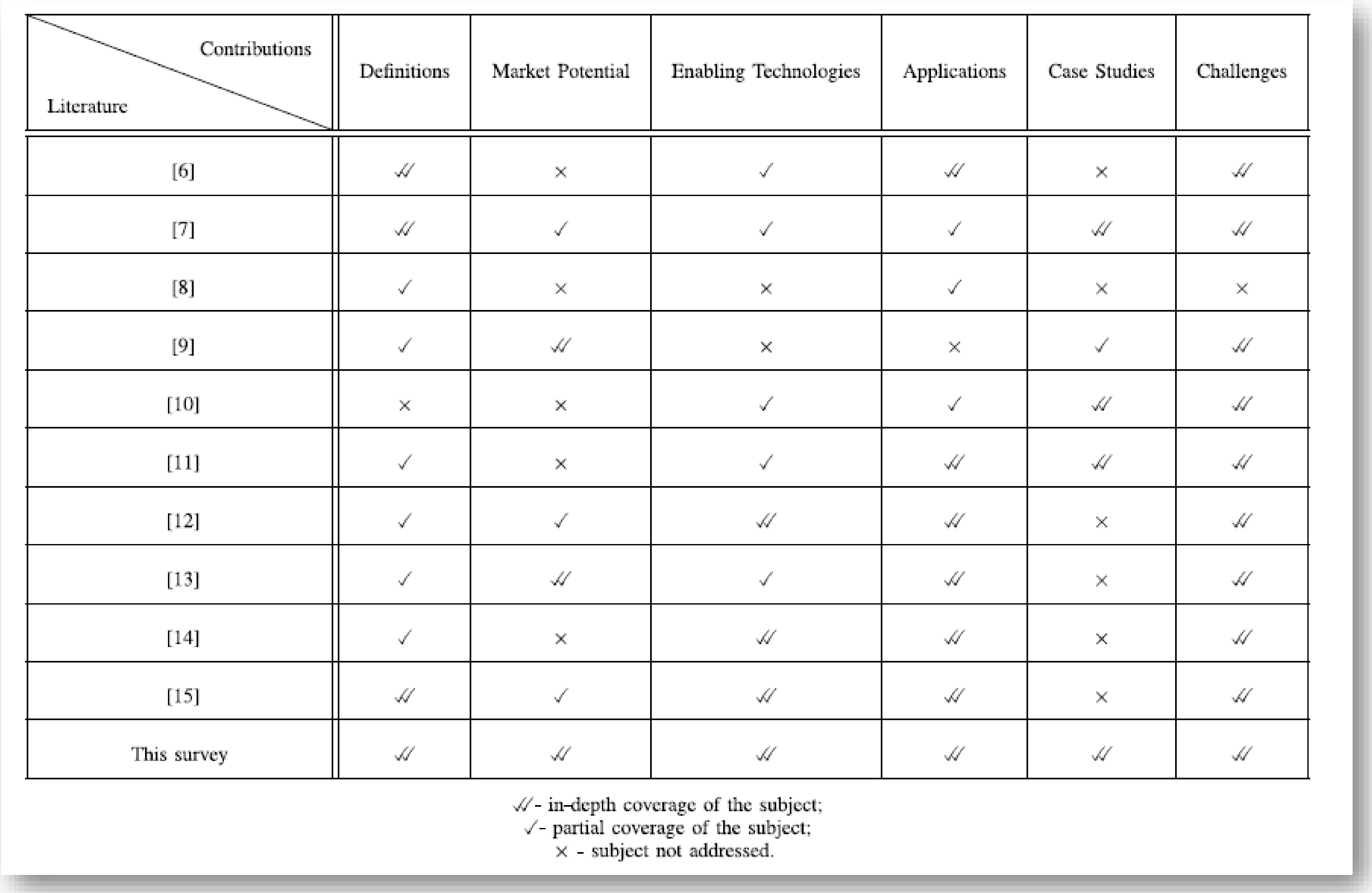
- **Biesinger et al [9]**. conducted a survey on the **necessity of a DT in the automotive industry's integration planning processes**, interviewing 22 production planners from various automotive manufacturing companies.
- The paper covers the demand of an easily accessible and configurable DT for the specific use-case of integration planning, but does not delve into the possible solutions or enabling technologies that could help implement a DT that is compliant with the definitions.
- **He et al. [10]** proposed a survey focused on the **monitoring and surveillance capabilities of the DT**, which is a dynamic digital replica of physical assets, processes, and systems.
- The authors do not emphasize the full extent of the DT definition, but present the technologies that enable it to become an **avant-garde methodology** for surveillance. An industrial use-case of the DT is presented, with technical advantages and challenges of implementing it for an ultra-high voltage converter station.

RELATED SURVEYS: CONTINUE – 3

- **Pires et al [11].** review the DT's definitions, enabling technologies, and applications, and provide a case-study of the concept. They also look at research efforts towards building a **DT for a UR3 collaborative robot**.
- **Rasheed et al [12].** created a comprehensive DT survey to **analyze** its value, applications, enabling technologies, and challenges, as well as potential **socio-economic impacts**.
- **Tao et al. analyze [13].** Introduce analysis of **50 papers** and **8 patents** related to the DT and describe its applicability in three main areas in the manufacturing sector: **product design, production, and prognostics and health management**.
- The paper draws its lessons from articles focused on the state of the art of DTs in the manufacturing industry.

RELATED SURVEYS: CONTINUE – 4

- ☐ **Huang et al [14]**. describe the **advantages of AI-driven DTs** in **smart manufacturing** and **advanced robotics**, such as facilitating production planning and control, quality control, dynamics control, predictive maintenance, and many other services. AI techniques enable DTs across these two domains.
- ☐ Fuller et al. in [15] propose an extensive survey on DT, focusing on **its integration with IoT** and **data analytics technologies**. The survey discusses the DT, its enabling technologies, and applications in three main use cases: **smart city, healthcare,** and **manufacturing**.
- ☐ The manuscript aims to complement the aforementioned articles in providing a complete view of the DT.



Contributions Literature	Definitions	Market Potential	Enabling Technologies	Applications	Case Studies	Challenges
[6]	✓✓	×	✓	✓✓	×	✓✓
[7]	✓✓	✓	✓	✓	✓✓	✓✓
[8]	✓	×	×	✓	×	×
[9]	✓	✓✓	×	×	✓	✓✓
[10]	×	×	✓	✓	✓✓	✓✓
[11]	✓	×	✓	✓✓	✓✓	✓✓
[12]	✓	✓	✓✓	✓✓	×	✓✓
[13]	✓	✓✓	✓	✓✓	×	✓✓
[14]	✓	×	✓✓	✓✓	×	✓✓
[15]	✓✓	✓	✓✓	✓✓	×	✓✓
This survey	✓✓	✓✓	✓✓	✓✓	✓✓	✓✓

✓✓- in-depth coverage of the subject;
✓- partial coverage of the subject;
× - subject not addressed.

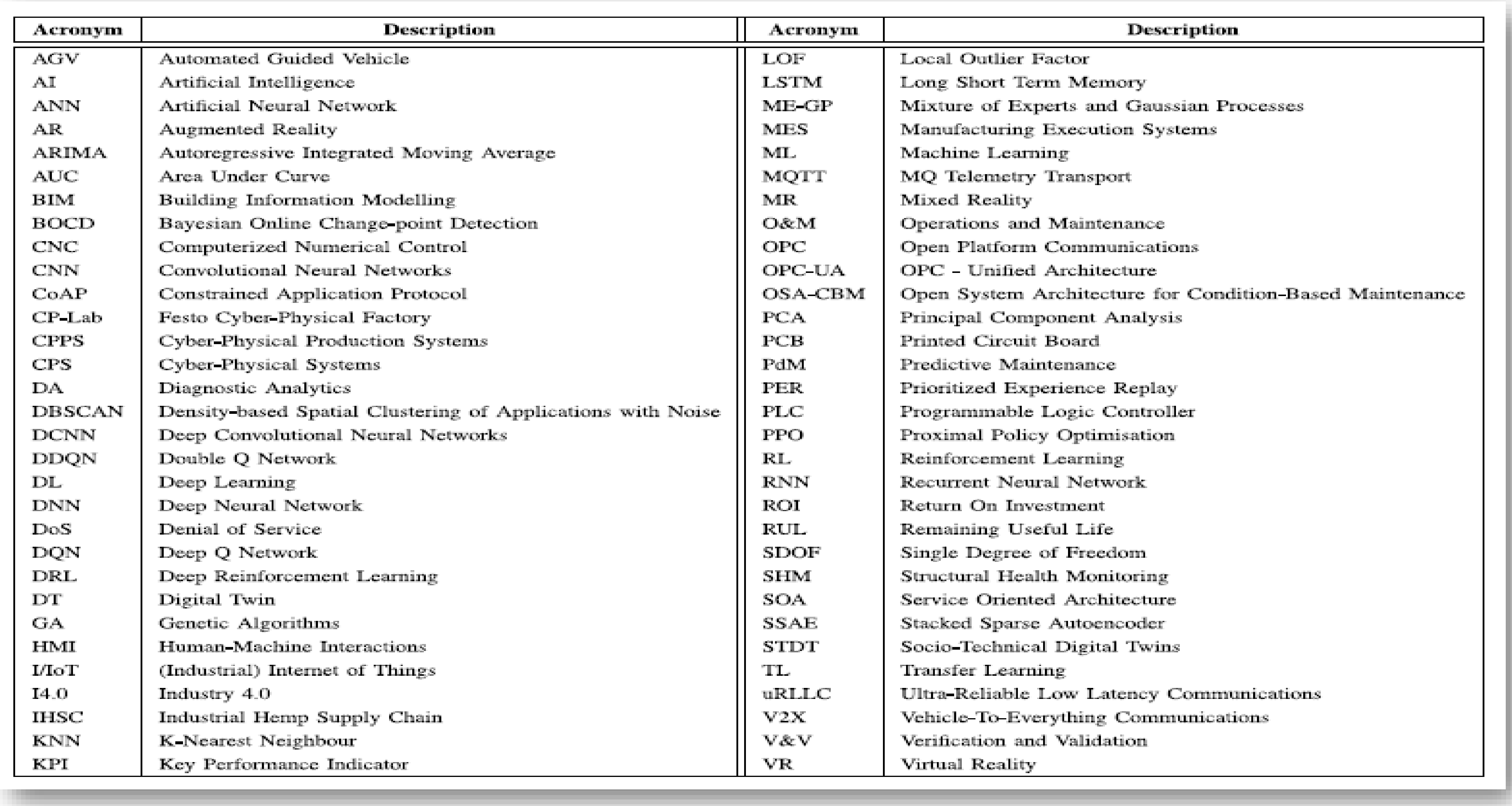
SURVEY CONTRIBUTIONS

This survey provides a comprehensive survey on the DT concept, enabling technologies, applications and use cases for deploying DTs across various industries. It covers:

- Overview of the DT definitions from the literature;
- Comprehensive discussions on the market potential of DT;
- The enabling technologies for DT are surveyed, such as: ML, cloud, fog and edge computing, IoT/IIoT, Cyber-Physical Systems, VR/AR, and modeling technologies;
- Existing solutions of DT frameworks are reviewed across three use cases examples, namely: smart factory, infrastructure, and future directions for 6th Generation Mobile Networks (6G). Then, we take a closer look at two DT services, irrespective of use case: anomaly detection and predictive maintenance;
- Three real use cases of DTs as applied to tea industry in India, Festo Cyber-Physical Factory in the United Kingdom, and structural health monitoring for Vietnam bridges are discussed in details;
- Lessons learned, remaining open challenges and future directions of DTs are identified.

SURVEY STRUCTURE

- This survey paper examines the **DT's potential** for market adoption, current trends, enabling technologies, frameworks, applications, case studies, lessons learned, current challenges, and future directions.
- **Section II** provides a review and comparison of existing definitions, **Section III** evaluates potential market adoption, **Section IV** delves into some of the most prominent DT enabling technologies, **Section V** explores various DT frameworks and applications, **Section VI** takes a closer look at three DT case studies, **Section VII** draws lessons from the survey, and **Section VIII** summarizes the conclusions.



Acronym	Description	Acronym	Description
AGV	Automated Guided Vehicle	LOF	Local Outlier Factor
AI	Artificial Intelligence	LSTM	Long Short Term Memory
ANN	Artificial Neural Network	ME-GP	Mixture of Experts and Gaussian Processes
AR	Augmented Reality	MES	Manufacturing Execution Systems
ARIMA	Autoregressive Integrated Moving Average	ML	Machine Learning
AUC	Area Under Curve	MQTT	MQ Telemetry Transport
BIM	Building Information Modelling	MR	Mixed Reality
BOCD	Bayesian Online Change-point Detection	O&M	Operations and Maintenance
CNC	Computerized Numerical Control	OPC	Open Platform Communications
CNN	Convolutional Neural Networks	OPC-UA	OPC – Unified Architecture
CoAP	Constrained Application Protocol	OSA-CBM	Open System Architecture for Condition-Based Maintenance
CP-Lab	Festo Cyber-Physical Factory	PCA	Principal Component Analysis
CPPS	Cyber-Physical Production Systems	PCB	Printed Circuit Board
CPS	Cyber-Physical Systems	PdM	Predictive Maintenance
DA	Diagnostic Analytics	PER	Prioritized Experience Replay
DBSCAN	Density-based Spatial Clustering of Applications with Noise	PLC	Programmable Logic Controller
DCNN	Deep Convolutional Neural Networks	PPO	Proximal Policy Optimisation
DDQN	Double Q Network	RL	Reinforcement Learning
DL	Deep Learning	RNN	Recurrent Neural Network
DNN	Deep Neural Network	ROI	Return On Investment
DoS	Denial of Service	RUL	Remaining Useful Life
DQN	Deep Q Network	SDOF	Single Degree of Freedom
DRL	Deep Reinforcement Learning	SHM	Structural Health Monitoring
DT	Digital Twin	SOA	Service Oriented Architecture
GA	Genetic Algorithms	SSAE	Stacked Sparse Autoencoder
HMI	Human-Machine Interactions	STDT	Socio-Technical Digital Twins
I/IoT	(Industrial) Internet of Things	TL	Transfer Learning
I4.0	Industry 4.0	uRLLC	Ultra-Reliable Low Latency Communications
IHSC	Industrial Hemp Supply Chain	V2X	Vehicle-To-Everything Communications
KNN	K-Nearest Neighbour	V&V	Verification and Validation
KPI	Key Performance Indicator	VR	Virtual Reality

DEFINITIONS OF DIGITAL TWIN

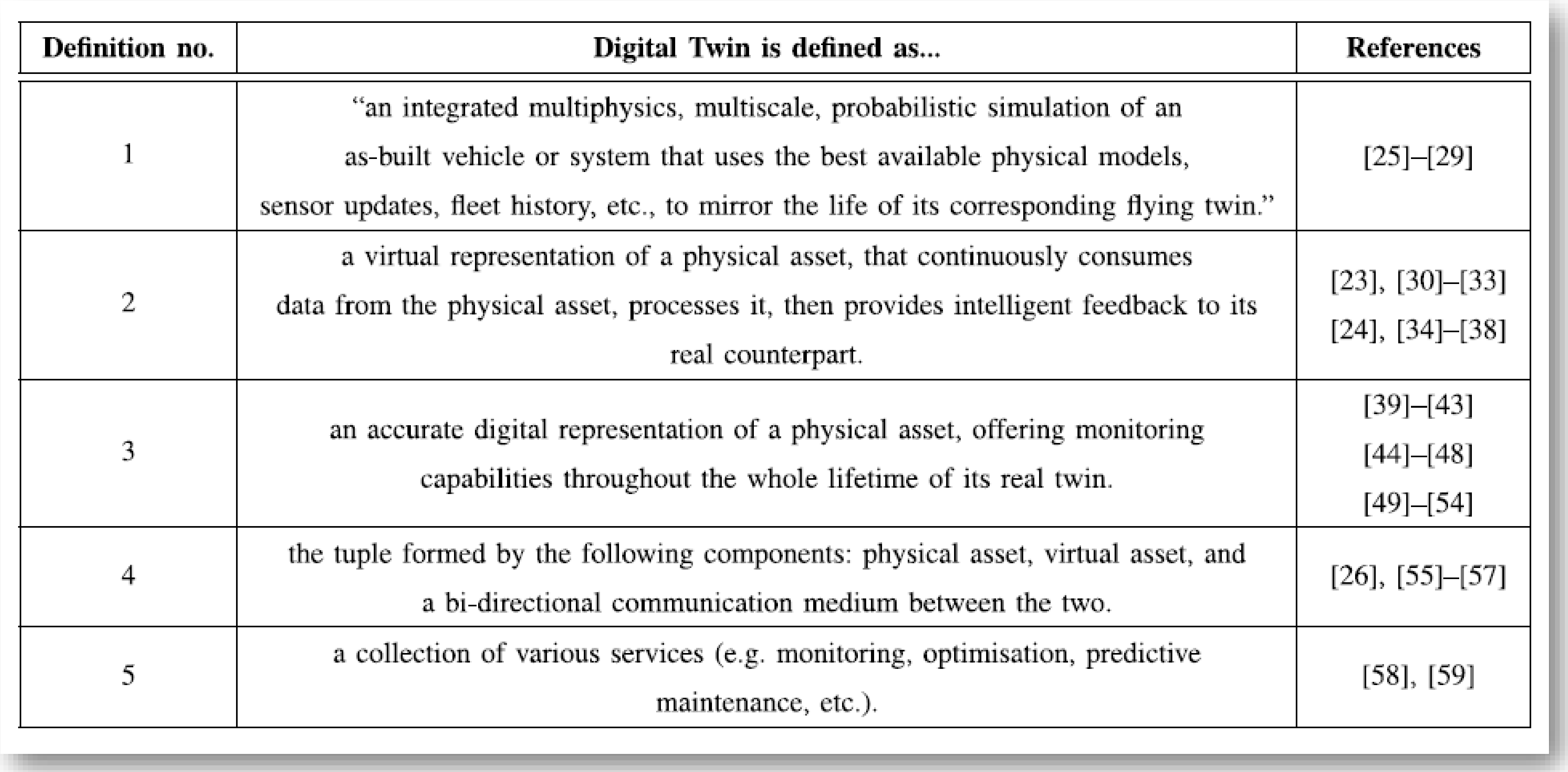
- The Digital Twin is not a new paradigm, having been introduced **more than 50 years ago** by **NASA's early space programmed**.
- The true precursor of this paradigm came to light during **NASA's Apollo 13 mission**, when an unexpected explosion caused a manned spacecraft to deviate from its intended trajectory.
- Mission Control was tasked to simulate the erratic behavior of the spacecraft and make optimal decisions to ensure its safe return on Earth. The engineers used spacecraft simulators, animated them with real data coming from the space-bound physical ship and its pilots, analyzed possible scenarios, and communicated optimal instructions to the stranded pilots to maneuver their ship back home safely. The mission was a success.
- **Michael Grieves** proposed a "**Mirrored Spaces Model**" in 2002 to drive forward the Product Lifecycle Management paradigm, which consisted of three pillars: **real space, virtual space, and the communication thread between them**.

DEFINITIONS OF DIGITAL TWIN: CONTINUE – 1

- The real space was represented by the physical spacecraft stranded in space, the virtual space by ground-based simulators, and the link between the two by continuous communication between Mission Control, the spacecraft, engineers, and pilots.
- The definition of the DT has been ambiguous, but implementations have been achieved with the support of common enabling technologies such as ML, TL, distributed computing, I/IoT, CPS, and VR/AR.
- The most important details in this text are the five definitions of the Digital Transaction (DT). These definitions are based on five approaches: the **first** definition is generic, the **second** definition is more comprehensive, the **third** definition completely ignores the bi-directional communication requirement, the **fourth** definition focuses entirely on the components of the DT, but does not hint towards the capabilities of a DT, and the **fifth definition** shifts its attention to the services provided by the DT but not on its structure and technologies that enable them.
- These definitions suggest that the DT is an intelligent digital model of a physical asset, with little to no emphasis on the interaction between the two, its requirements, and limitations.

DEFINITIONS OF DIGITAL TWIN: CONTINUE – 2

- The DT of an autonomous car requires **ultra-low latency** communication between the real and virtual twins, large data storage capacity, high processing power to reduce **data-to-insight** delays, and high-fidelity virtual rendering of the car and its environment.
- The five definitions of the DT differ in how they describe the feedback loop between the two entities. The **first** and **third definitions** claim that the DT only mirrors the life of its twin, while the **second definition** does not mention the DT's requirements that might differ from use-case to use-case. The **fourth definition** makes no mention of the DT's use-case at all, while the **fifth definition** focuses entirely on the use-case and services the DT can provide.
- The use-case's requirements and the DT components are only implied via the definitions of the services themselves, and not explicitly stated as DT characteristics.



Definition no.	Digital Twin is defined as...	References
1	“an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.”	[25]–[29]
2	a virtual representation of a physical asset, that continuously consumes data from the physical asset, processes it, then provides intelligent feedback to its real counterpart.	[23], [30]–[33] [24], [34]–[38]
3	an accurate digital representation of a physical asset, offering monitoring capabilities throughout the whole lifetime of its real twin.	[39]–[43] [44]–[48] [49]–[54]
4	the tuple formed by the following components: physical asset, virtual asset, and a bi-directional communication medium between the two.	[26], [55]–[57]
5	a collection of various services (e.g. monitoring, optimisation, predictive maintenance, etc.).	[58], [59]

DEFINITIONS OF DIGITAL TWIN: CONTINUE – 3

- ☐ The Digital Twin (DT) is a self-adapting, self-regulating, self monitoring, and self-diagnosing system-of-systems with the following properties: **1.** it is characterized by a symbiotic relationship between a physical entity and its virtual representation, **2.** its fidelity, rate of synchronization, and choice of enabling technologies are tailored to its envisioned use cases, and **3.** it supports services that add operational and business value to the physical entity.
- ☐ This alternative provides a better understanding of the DT concept, as it gives a precise indication of what its components are, how they interact, how their interaction is leveraged, how accurate and synchronized the virtual asset should be, and what technologies should be used to build it.
- ☐ The "**self-X**" constructs distinguish a true DT from digital models and shadows, and emphasize the usefulness of a DT in I4. These traits include self-adapting, self-regulating, self-monitoring, and self-diagnosing.

DEFINITIONS OF DIGITAL TWIN: CONTINUE – 4

- **Self-adapting** means that the DT automatically reacts to changes in its real twin's environment and configuration, but should do so in a way that ensures operational excellence.
- **Self-regulating** means that the changes a DT undergoes should not exceed the physical twin's limitations for the sake of maximizing its performance measures.
- **Self-monitoring means** the DT is always aware of its environment and configuration.
- **Self-diagnosing** means the DT should be able to assess its own health and know when and why it is no longer able to maintain optimal operations.

MARKET POTENTIALS AND TRENDS

- The Digital Transformation (DT) is a versatile technology that can be successfully applied to various domains, but businesses are reluctant to implement it due to the lack of **ROI**. This section will examine how the DT market has leveraged its aptitudes and whether their results predict a good omen for the future of the DT.
- **IBM** valued the DT market at **USD 3.1 billion in 2020** and predicted significant adoption and economic growth. IBM's case studies show encouraging returns and cost optimizations for DT implementations in manufacturing and smart buildings.
- **ASTRI** used DTs to validate **software packages before deployment**, reducing development costs and expediting deployment by 40%. University of California San Francisco implemented DTs for a branch of the Mission Bay Hospital to reduce diagnosis and repair process from 2-3 days to just a few hours.

MARKET POTENTIALS AND TRENDS: CONTINUE – 1

- ❑ **Ansys** and **Mecuris** have used DTs to reduce product testing costs, while Jet Towers have implemented DTs of modular wireless towers to reduce installation and design time.
- ❑ **General Electric** and **Spirent** are leading the DT market in power systems and telecommunications, respectively.
- ❑ General Electric's solution claims to reduce startup time by 50%, maintenance costs by 10%, deliver up to $5 million additional MWhr, and save costs on outages of up to $150 million per year.
- ❑ Spirent propose leveraging the DT for use cases such as cellular Vehicle-to-Everything (V2X) virtual drive testing, private 5G networks for smart factories, and testing and design for Communications Service Providers.
- ❑ The DT market is expected to grow from $3.2 billion in 2020 to $48.27 billion by 2026, with a Compound Annual Growth Rate of 58%. However, industry-agnostic adoption is only 5% of enterprises, and the authors are optimistic that the DT should pave the way to I4.

DIGITAL TWIN: ENABLING TECHNOLOGIES

- The Digital Twin (DT) is a system-of-systems that combines several enabling technologies to construct an intelligent virtual representation of a physical entity and support a continuous two-way feedback loop between the twins.
- This section will explore the most common enabling technologies of the DT and provide insight into how researchers from various industries have chosen algorithms and frameworks that were fitting to their use cases.

MACHINE LEARNING

- DT is a new kind of specialized intelligence that is able to understand large amounts of numerical data and **draw domain-specific** conclusions faster than a human expert.
- ML techniques represent the foundation of a DT, allowing it to infer meaningful and actionable information from data generated by its physical twin and its environment.
- Researchers have used various ML algorithms in DT implementations, including traditional ML, DL, supervised ML, unsupervised ML, classification ML, regression ML, and RL.
- ML models are used to solve optimization problems, and one common approach is to employ **data-driven models** to minimize where the DT of a Mobile Edge Computing system is located. In [40], a Deep Neural Network (DNN) was used to maximize energy consumption efficiency.
- In [55], four ML algorithms (Random Forest, AdaBoost, LightGBM, and XGBoost) were able to learn from the equipment's sensor data and optimize production yield in the petrochemical industry. This approach is especially common in literature focused on RL, where the algorithm learns by trying to maximize a reward function.

MACHINE LEARNING: CONTINUE – 1

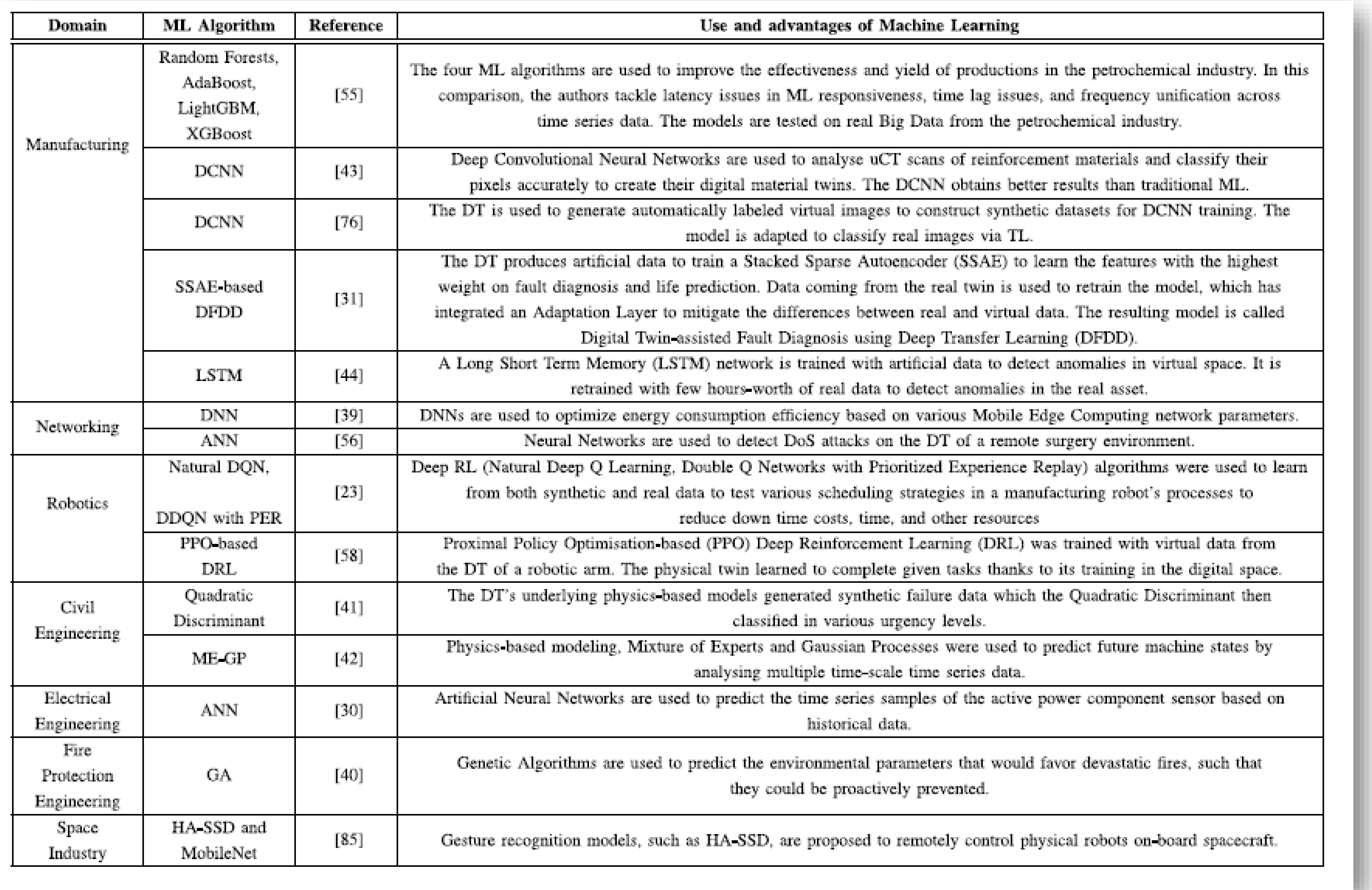
- ML is used to make **predictions about the future behavior of physical assets**, but is perceived as black-boxes due to lack of transparency. To address this, researchers have looked for ways to integrate both physics-based and data-driven models into the DT.
- The authors in [42] combined these two approaches to enable a **prognosis service** that predicts the future parameters of a physical asset, even though said parameters evolved at different time scales.
- The ML models, Mixture of Experts and Gaussian Processes (ME-GP), combined the extracted information to predict future behaviors of each time series parameter.
- ML is being used to protect the connection between the physical and virtual worlds, detecting and preventing Denial of Service (DoS) attacks, and creating digital replicas of fibrous materials from real and synthetic images. This is an example of ML being used to build DTs.

MACHINE LEARNING: CONTINUE – 2

- DTs can be used to generate artificial training data for ML models, but for them to generalize well on real data, the distribution of the synthetic data must closely resemble the real data from the test set.
- TL is a workaround for this challenge, requiring that the distributions of artificial and real data be somewhat similar, such that only a small amount of real data is needed to make the model generalize well once deployed in production.
- ML can be used in DT implementations for remote control assistance, such as remote surgery and space station maintenance. In the latter paper, the authors proposed the Hierarchical Attention Single-Shot Detector Network (HA-SSD) for astronaut gesture recognition.
- The system is based on the MobileNet architecture and is ideal for space station DTs where cameras and surveillance equipment can detect and monitor faces, human postures, gestures and body language.

MACHINE LEARNING: CONTINUE – 3

- Table (See Next Slide) summarizes the findings of integrating ML into DT. It is important to note that most of the efforts towards DT implementation come from the manufacturing industry, but the versatility of the technology makes it a promising tool for other domains as well.
- It is the vast array of existing and up-and-coming ML and DL algorithms that gives the DT its versatility, but its reliance on data-driven analytics imposes challenges.
- **Traditional ML** models are built upon a sequence of carefully engineered functional blocks that are tailored to increase efficiency, while **end-to-end DL** techniques require significant amounts of data for training and tuning. **Generative ML models** can be used to create artificial data to compensate for the lack of real data, but this could lead to bias in predictions if the two distributions are not aligned.



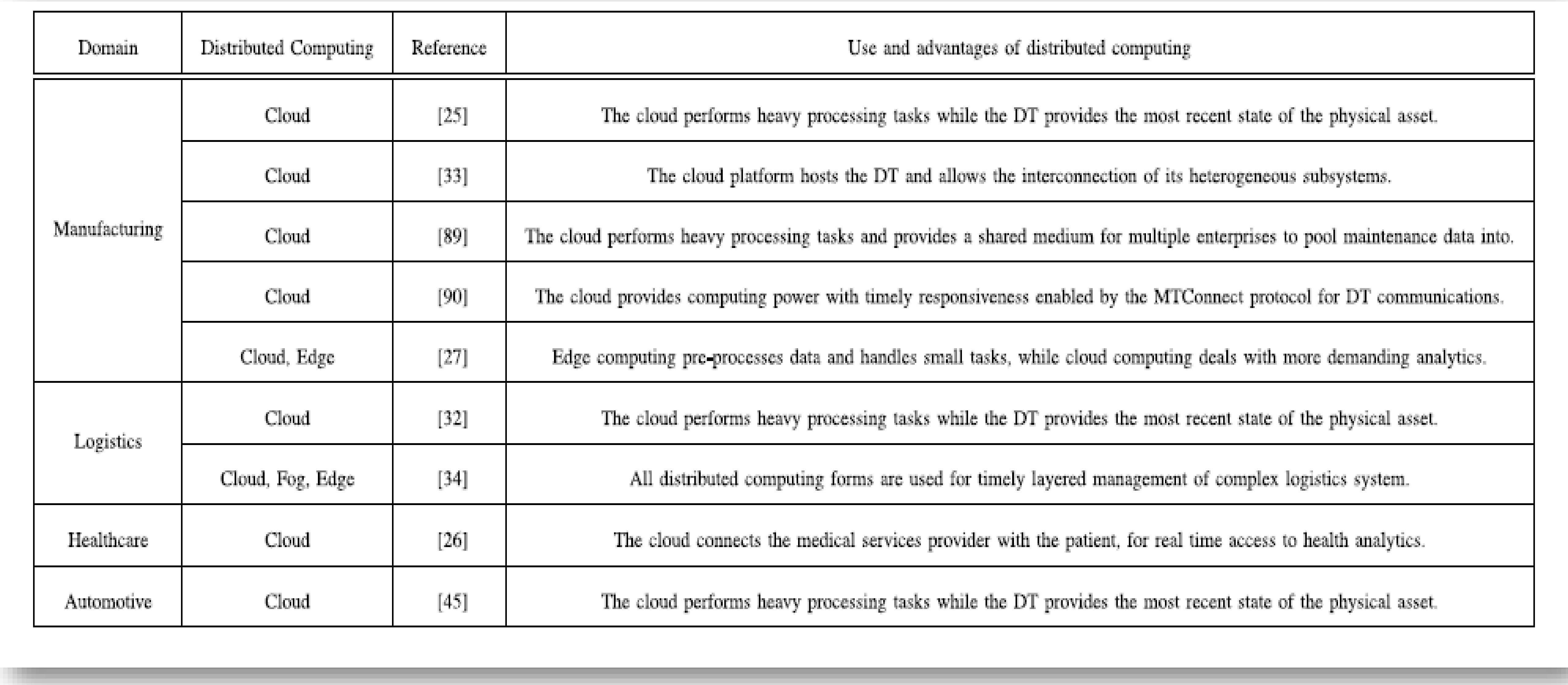
Domain	ML Algorithm	Reference	Use and advantages of Machine Learning
Manufacturing	Random Forests, AdaBoost, LightGBM, XGBoost	[55]	The four ML algorithms are used to improve the effectiveness and yield of productions in the petrochemical industry. In this comparison, the authors tackle latency issues in ML responsiveness, time lag issues, and frequency unification across time series data. The models are tested on real Big Data from the petrochemical industry.
	DCNN	[43]	Deep Convolutional Neural Networks are used to analyse uCT scans of reinforcement materials and classify their pixels accurately to create their digital material twins. The DCNN obtains better results than traditional ML.
	DCNN	[76]	The DT is used to generate automatically labeled virtual images to construct synthetic datasets for DCNN training. The model is adapted to classify real images via TL.
	SSAE-based DFDD	[31]	The DT produces artificial data to train a Stacked Sparse Autoencoder (SSAE) to learn the features with the highest weight on fault diagnosis and life prediction. Data coming from the real twin is used to retrain the model, which has integrated an Adaptation Layer to mitigate the differences between real and virtual data. The resulting model is called Digital Twin-assisted Fault Diagnosis using Deep Transfer Learning (DFDD).
	LSTM	[44]	A Long Short Term Memory (LSTM) network is trained with artificial data to detect anomalies in virtual space. It is retrained with few hours-worth of real data to detect anomalies in the real asset.
Networking	DNN	[39]	DNNs are used to optimize energy consumption efficiency based on various Mobile Edge Computing network parameters.
	ANN	[56]	Neural Networks are used to detect DoS attacks on the DT of a remote surgery environment.
Robotics	Natural DQN, DDQN with PER	[23]	Deep RL (Natural Deep Q Learning, Double Q Networks with Prioritized Experience Replay) algorithms were used to learn from both synthetic and real data to test various scheduling strategies in a manufacturing robot's processes to reduce down time costs, time, and other resources
	PPO-based DRL	[58]	Proximal Policy Optimisation-based (PPO) Deep Reinforcement Learning (DRL) was trained with virtual data from the DT of a robotic arm. The physical twin learned to complete given tasks thanks to its training in the digital space.
Civil Engineering	Quadratic Discriminant	[41]	The DT's underlying physics-based models generated synthetic failure data which the Quadratic Discriminant then classified in various urgency levels.
	ME-GP	[42]	Physics-based modeling, Mixture of Experts and Gaussian Processes were used to predict future machine states by analysing multiple time-scale time series data.
Electrical Engineering	ANN	[30]	Artificial Neural Networks are used to predict the time series samples of the active power component sensor based on historical data.
Fire Protection Engineering	GA	[40]	Genetic Algorithms are used to predict the environmental parameters that would favor devastatic fires, such that they could be proactively prevented.
Space Industry	HA-SSD and MobileNet	[85]	Gesture recognition models, such as HA-SSD, are proposed to remotely control physical robots on-board spacecraft.

CLOUD FOG AND EDGE COMPUTING

- DT can be used to **mirror systems** across the whole spectrum of complexity, from unitary elements to an entire fleet of aircraft. Virtualization of composite heterogeneous machines or services requires heavy computational prowess, which requires distributed and parallel computing.
- This section will review how researchers have integrated distributed computing into their DT implementations, with an emphasis on the reason why this enabling technology was mandatory for the works' use-cases.
- Table (See slide 37) provides an overview of the papers reviewed in this section, which show that distributed computing and DT have been combined in works mostly pertaining to the manufacturing sector.
- Additionally, papers focusing on DTs for logistics are mainly created to help the logistics departments of the manufacturing industry.

CLOUD FOG AND EDGE COMPUTING: CONTINUE – 1

- Cloud computing and DT create a **prosperous environment for complex simulations**, multi-variable analysis, DL-based analytics, and Big Data storage.
- The cloud platform acts as the data warehouse and provides heavy-processing capabilities, while the DT deals with synchronizing physical and virtual assets.
- In the **healthcare industry**, the cloud represents a shared information platform between the medical service provider and the patients, while in the manufacturing domain it can serve as a common medium to share data regarding failure modes and maintenance needs of similar equipment.
- **Hu et al**. [90] reduce the cloud workload by using the MTConnect protocol and a Knowledge Resource Centre to manage all communications with the cloud-hosted DT. To avoid over-dependence on the cloud, more forms of distributed computing are used to manage **complex logistics and manufacturing systems**.



Domain	Distributed Computing	Reference	Use and advantages of distributed computing
Manufacturing	Cloud	[25]	The cloud performs heavy processing tasks while the DT provides the most recent state of the physical asset.
	Cloud	[33]	The cloud platform hosts the DT and allows the interconnection of its heterogeneous subsystems.
	Cloud	[89]	The cloud performs heavy processing tasks and provides a shared medium for multiple enterprises to pool maintenance data into.
	Cloud	[90]	The cloud provides computing power with timely responsiveness enabled by the MTConnect protocol for DT communications.
	Cloud, Edge	[27]	Edge computing pre-processes data and handles small tasks, while cloud computing deals with more demanding analytics.
Logistics	Cloud	[32]	The cloud performs heavy processing tasks while the DT provides the most recent state of the physical asset.
	Cloud, Fog, Edge	[34]	All distributed computing forms are used for timely layered management of complex logistics system.
Healthcare	Cloud	[26]	The cloud connects the medical services provider with the patient, for real time access to health analytics.
Automotive	Cloud	[45]	The cloud performs heavy processing tasks while the DT provides the most recent state of the physical asset.

INTERNET OF THINGS

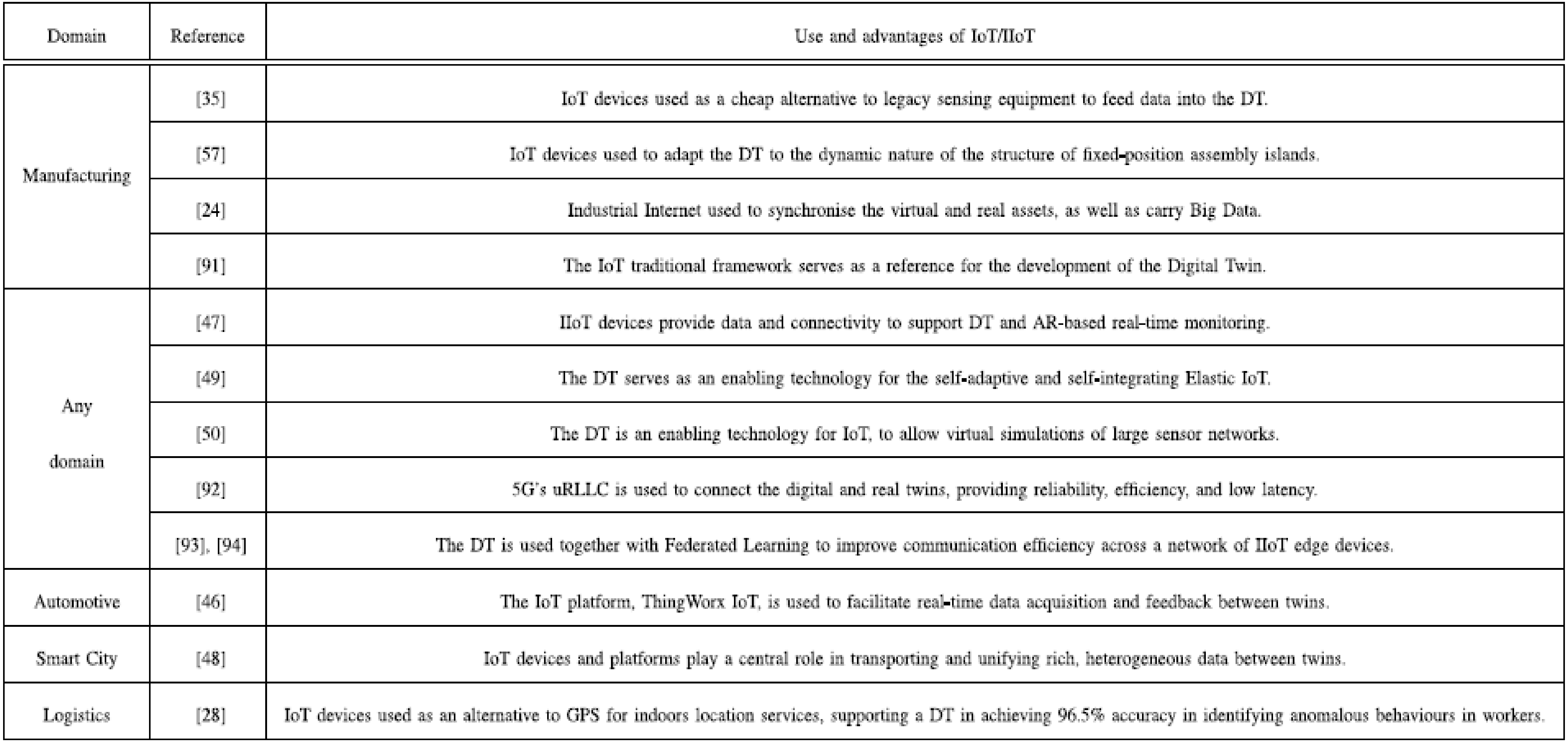
- The research communities of academia and industry recognize the DT as a system formed by three functional blocks: **1.** the physical asset, **2.** its virtual counterpart, **3.** and the communication medium.
- This section will focus on the two-way connection between the digital and real twins, and the recent literature works that detail how this connection benefits the implementation of the DT.
- Table (See Slide 41) provides an overview of the articles discussed, as well as their target domain and main contributions.
- The Internet of Things and the Industrial Internet of Things are enabling technologies that can converge virtuality and reality, enabling data mining and analytics through distributed computing frameworks.

INTERNET OF THINGS: CONTINUE – 1

- IIoT devices, such as smart sensors, RFID tags, and smart wearables, are useful and cheap data sources that can be used to reduce manufacturing uncertainty and complexity, optimize the functioning of power equipment switchgear, provide PdM for automotive brake pads, and visualize in real time the stress endured by metal shelving brackets.
- Other use-cases benefit from these technologies, such as virtualizing and visualizing cities, allowing structural simulations for hazards prevention, and remotely managing safety issues in the workplace.
- The DT can act as a **supporting pillar** for the IoT by providing a self-adaptive and self-integrating digital abstraction of the IoT devices, or by allowing virtual simulations of large sensor networks. In the context of IIoT, equipping edge devices with ML solutions can be challenging due to limited resources and concerns about communications with the cloud.
- To address this, the authors proposed building a DT of the Edge Network that was able to leverage Federated Learning (FL) to re-train aggregated models locally, optimize communication efficiency, and store the aggregated model parameters on the Base Station.

INTERNET OF THINGS: CONTINUE – 2

- IoT contributes to DT development by providing a platform that can understand and translate data from multiple protocols. IoT devices are usually built with certain communication standards in mind, such as MQTT, CoAP, MTConnect, OPC-UA, or 5G uRRLC.
- The choice of IoT devices, communication protocols, and IoT platforms can influence the synchronization rate between the real and virtual twins.
- For time-sensitive applications, the communication link between the two entities should include secure uRLLC, while other use-cases where synchronization latency is not necessarily a problem, like rarely-used manufacturing equipment, this requirement is not so stringent.



Domain	Reference	Use and advantages of IoT/IIoT
Manufacturing	[35]	IoT devices used as a cheap alternative to legacy sensing equipment to feed data into the DT.
	[57]	IoT devices used to adapt the DT to the dynamic nature of the structure of fixed-position assembly islands.
	[24]	Industrial Internet used to synchronise the virtual and real assets, as well as carry Big Data.
	[91]	The IoT traditional framework serves as a reference for the development of the Digital Twin.
Any domain	[47]	IIoT devices provide data and connectivity to support DT and AR-based real-time monitoring.
	[49]	The DT serves as an enabling technology for the self-adaptive and self-integrating Elastic IoT.
	[50]	The DT is an enabling technology for IoT, to allow virtual simulations of large sensor networks.
	[92]	5G's uRLLC is used to connect the digital and real twins, providing reliability, efficiency, and low latency.
	[93], [94]	The DT is used together with Federated Learning to improve communication efficiency across a network of IIoT edge devices.
Automotive	[46]	The IoT platform, ThingWorx IoT, is used to facilitate real-time data acquisition and feedback between twins.
Smart City	[48]	IoT devices and platforms play a central role in transporting and unifying rich, heterogeneous data between twins.
Logistics	[28]	IoT devices used as an alternative to GPS for indoors location services, supporting a DT in achieving 96.5% accuracy in identifying anomalous behaviours in workers.

CYBER – PHYSICAL SYSTEM

- The term Cyber-Physical Systems (CPS) has gained attention from academia and industry, but there are two definitions that fall under the span of the CPS abbreviation. In the original vision of CPS, the physical space is represented by an ecosystem of physical equipment, sensors, actuators, and human operators.
- The cyber elements are virtual representations of the physical components and offer a layer of intelligence that provides self-configuration, self-adaptation, and self-preservation to each physical instance.
- This interpretation of CPS leaves a blurry boundary between CPS and DTs, as they boast similar features and advantages and represent the smooth convergence between reality and virtuality. A study detailing a comparison and correlation between the two paradigms has been conducted in [36].

CYBER – PHYSICAL SYSTEM: CONTINUE – 1

- ☐ CPS refers to physical systems with varying levels of complexity that are equipped with built-in sensors, actuators, networking and computation capabilities, and controlled digitally via computer-based algorithms.
- ☐ They are I4. 0-ready physical equipment that are proficient in reliable data acquisition, process optimization with feedback inputs, and improved built-inmonitoring and control capabilities. They are an asset for DTs to gather data securely from the physical processes and perform regulatory control operations at the edge.
- ☐ CPS-specific Service-Oriented Architecture (SOA) is used to build the DT and act as Cyber-Physical System Nodes in the virtual ecosystem.

CYBER – PHYSICAL SYSTEM: CONTINUE – 2

- The most important details in this text are the contributions and advantages of CPS-integrating DTs, which are used in the manufacturing industry to turn conventional factory equipment into CPS by populating them with sensors and connecting them to their virtual twins.
- The SOA, which is a founding principle of CPS, serves as a decoupling strategy that allows DT services to interact independently and efficiently.

Domain	Reference	Use and advantages of CPS
Manufacturing	[59]	A four-layer CPS architecture is used to integrate a tri-model Digital Twin (Digital Model, Computational Model, and Graph-based Model)
	[51]	A five-layer CPS architecture (data store, pre-processing, model & algorithms, analysis, user interface) is used to integrate a Digital Twin.
	[29]	The Service Oriented Architecture of CPS is used to facilitate the integration of DT in CPPS.
	[37]	Digital Twins are used to virtually manage individual components' issues (data ownership, version management, etc.) in a System of Systems.
	[52]	Functional Mock-Up Units are used to standardize the connection between a CPS and its DT, allowing for facile integration of physical systems in CPS.
	[38]	The CPS-specific MES software controls the physical CPS and communicates with the Matlab-based virtual twin.
	[54]	The DT is built upon an add-on software and communication infrastructure setup that controls, monitors and connects a real material-handling system with a simulation-based decision support.
Logistics	[53]	The DT incorporates the predicted machine health into the production scheduling algorithm (Genetic Algorithm) to optimize logistics tasks to avoid failure and prolong machine lifetime.

VIRTUAL REALITY AND AUGMENTED REALITY

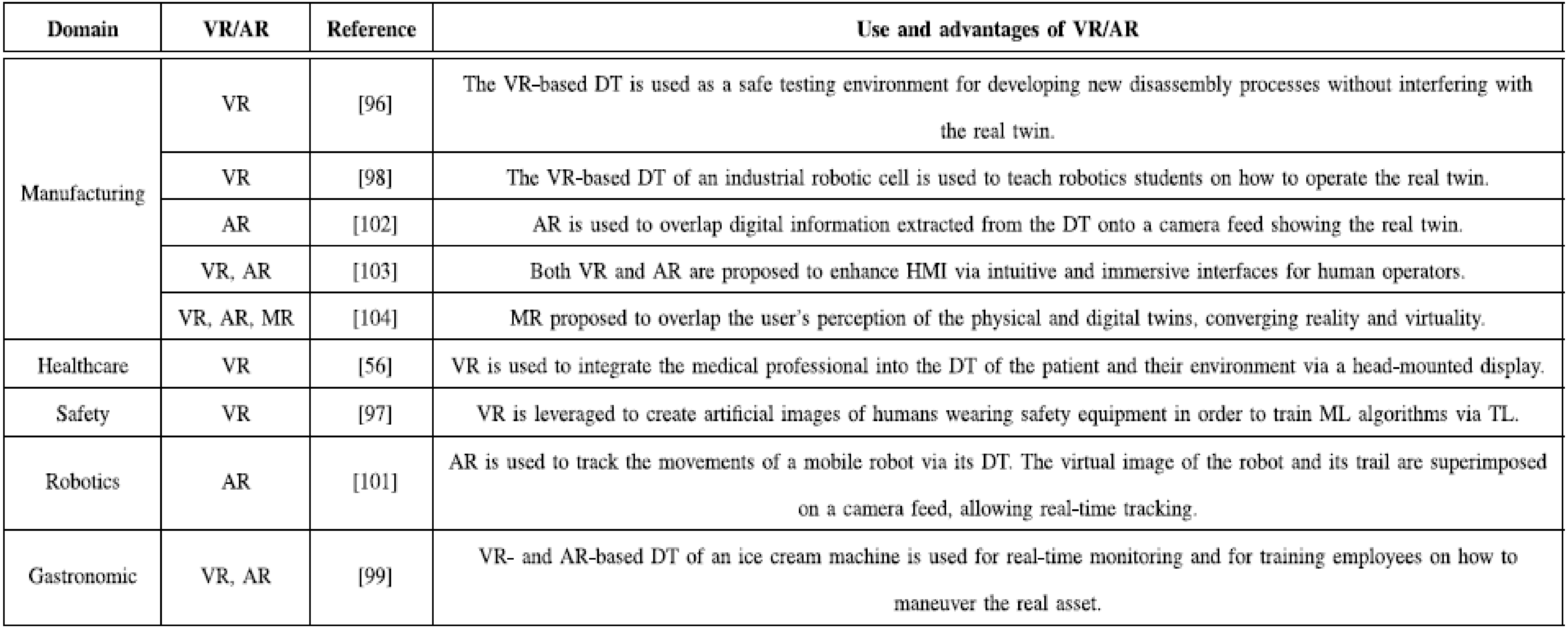
- The Digital Twin’s goal of virtuality and reality convergence seems to perfectly align with the driver behind two developing technologies: Virtual Reality and Augmented Reality.
- Indeed, VR aims to improve Human-Machine Interactions (HMI) via 3D computer-generated simulations with which the user can intuitively interact through wearable electronic devices. In other words, VR can help immerge human operators into a digital environment.
- On the other hand, AR technologies make use of wearable devices render 3D digital images onto a real-world background. In essence, AR helps bring virtual information in a physical environment. This section will explore how researchers have leveraged these two cutting-edge technologies to drive forward the DT paradigm.
- **Laaki et al.** [56] created a DT of a remote surgery environment that can be accessed via VR and wearable devices to control a virtual robotic arm. The DT synchronizes the real and virtual twins of the robotic arm, allowing users to directly and intuitively control the physical asset via its DT.

VIRTUAL REALITY AND AUGMENTED REALITY: CONTINUE – 1

- VR enables human operators to interact with virtual twins of industrial equipment without interrupting the normal functioning of the real entities.
- This allows engineers to devise new Circular Economy strategies, create high-quality artificial training sets, and have students and trainees learn how to operate the physical twin by immersive interacting with and practicing on their DTs.
- AR technologies enable quick access to DT interfaces by superimposing virtual data and images onto the camera feed when the camera is pointed at the physical twin. This allows human operators to dynamically monitor DTs without having to connect to the computer.

VIRTUAL REALITY AND AUGMENTED REALITY: CONTINUE – 2

- The VR/AR-enabled DT can address three current challenges in HMI development: highfidelity virtual representations of physical assets, availability of both real and simulated data, and intuitive interfaces for human operators.
- However, neither technology is enough for a complete merge between the real and virtual worlds. Mixed Reality (MR) technologies combine the advantages of both VR and AR to bring digital models in the physical world and simulate their processes under real circumstances.
- Table (See next Slide) summarizes the main domains where VR/AR/MR technologies have enabled the DT to provide immersive HMI, training and monitoring.



Domain	VR/AR	Reference	Use and advantages of VR/AR
Manufacturing	VR	[96]	The VR-based DT is used as a safe testing environment for developing new disassembly processes without interfering with the real twin.
	VR	[98]	The VR-based DT of an industrial robotic cell is used to teach robotics students on how to operate the real twin.
	AR	[102]	AR is used to overlap digital information extracted from the DT onto a camera feed showing the real twin.
	VR, AR	[103]	Both VR and AR are proposed to enhance HMI via intuitive and immersive interfaces for human operators.
	VR, AR, MR	[104]	MR proposed to overlap the user's perception of the physical and digital twins, converging reality and virtuality.
Healthcare	VR	[56]	VR is used to integrate the medical professional into the DT of the patient and their environment via a head-mounted display.
Safety	VR	[97]	VR is leveraged to create artificial images of humans wearing safety equipment in order to train ML algorithms via TL.
Robotics	AR	[101]	AR is used to track the movements of a mobile robot via its DT. The virtual image of the robot and its trail are superimposed on a camera feed, allowing real-time tracking.
Gastronomic	VR, AR	[99]	VR- and AR-based DT of an ice cream machine is used for real-time monitoring and for training employees on how to maneuver the real asset.

MODELING METHODOLOGIES

- The umbrella of modeling methodologies covers a range of frameworks and software meant to guide developers towards building a core component of the DT: the virtual representation of the physical entity. The challenge to overcome is the interdisciplinary and use case-specific nature of the DT, which makes it difficult to define.
- An architecture for the manufacturing industry is proposed, which breaks down the DT into three constituents: product DT, process DT, and operation DT. A different modeling methodology, presented in [107], summarizes a manufacturing DT as the synchronization between 3D modeling and mechanism modeling.

MODELING METHODOLOGIES: CONTINUE – 1

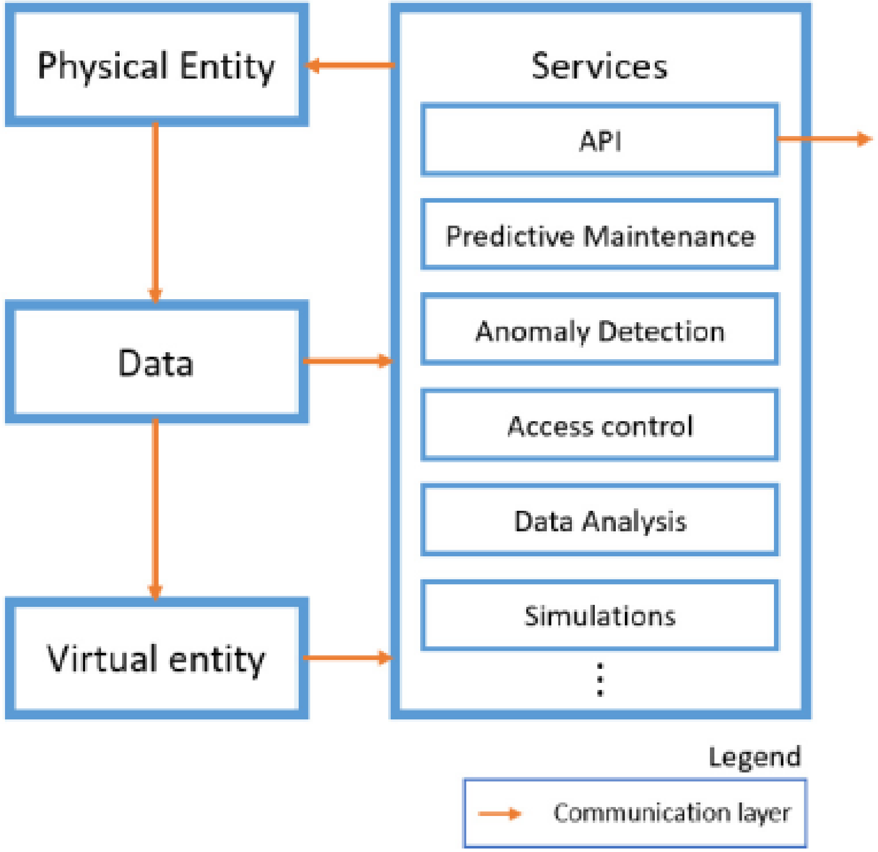
- ❑ Researchers in the field have come up with DT frameworks that abstract away from the use case-specific details of implementing. The authors in [108] claim that a DT only requires two main components to be whole: a virtual representation of the physical entity and an API.
- ❑ Other works suggest that other dimensions can be added to the DT, such as data storage, access control, methods, events, and a human-machine interface.
- ❑ Riedelsheimer et al. [110] proposed a methodology for building DTs for already-built, complex, inter-disciplinary physical objects, with the goal of creating the DT of a smart factory able to manufacture customizable products.

MODELING METHODOLOGIES: CONTINUE – 1

- The 5-dimensional DT is a common approach to modeling methodologies that can be found in the literature. Tao et al. proposed the five dimensions of the DT, which are physical entity, virtual entity, communication, data, and services.
- Wang et al. [112] proposed a System Design Digital Twin which aims to reduce the complexity of model-based system engineering by closing the gap between the physical and theoretical design processes. GHOST (Geometry, History, Object, Snapshot, Topology) is an expansion of the data element of Tao's architecture.
- Wu et al. presented a methodology for building 5D DT models that is supported by an improved version of the TRIZ function model.
- Other existing architectures partially overlap with Tao's methodology, such as Bazaz et al.'s data store layer, primary processing layer, model and algorithms layer, analysis layer, and user interface component.

MODELING METHODOLOGIES: CONTINUE – 2

- Abstract modeling methodologies have converged around Tao's 5D model, but implementation details and technologies remain use case-specific.



OPINION ABOUT THE PAPER

- Digital twins are virtual models of physical objects or systems that can be used for simulation, monitoring, and optimization. They are enabled by technologies such as IoT, cloud computing, AI, and data analytics.
- The paper highlights some of the challenges and issues related to digital twins, such as data privacy and security, standardization, scalability, and integration with legacy systems. It also discusses some of the emerging trends in this field, such as digital twin ecosystems and the use of digital twins for autonomous systems.
- Digital Twins is an emerging field that has gained significant attention in recent years, particularly in the context of Industry 4.0 and the Internet of Things (IoT). Digital Twins refer to virtual models or replicas of physical systems, products, or processes that are created and maintained throughout their entire lifecycle. Digital Twins can help in various applications, such as predictive maintenance, optimization, and decision-making.
- The paper concludes by discussing some of the future prospects of digital twins, including their potential impact on industries such as manufacturing, healthcare, and transportation. It also highlights the need for further research in this field to address some of the remaining challenges and to fully realize the potential of digital twins.

Thank You