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Digital Twin as a Service (DTaaS) in Industry 4.0: An Architecture Reference Model

Shohin Aheleroff [a,*], Xun Xu [a], Ray Y. Zhong [b], Yuqian Lu [a]

[a] Department of Mechanical Engineering, The University of Auckland, New Zealand
[b] Department of Industrial and Manufacturing Systems, The University of Hong Kong, Hong Kong

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ABSTRACT

Recent findings have shown that Digital Twin served multiple constituencies. However, the dilemma between the scope and scale needs a sophisticated reference architecture, a right set of technologies, and a suitable business model. Most studies in the Digital Twin field have only focused on manufacturing and proposed explicit frameworks and architecture, which faced challenges to support different integration levels through an agile process. Besides, no known empirical research has focused on exploring relationships between Digital Twin and mass individualization. Therefore, the principal objective of this study was to identify suitable Industry 4.0 technologies and a holistic reference architecture model to accomplish the most challenging Digital Twin enabled applications. In this study, a Digital Twin reference architecture was developed and applied in an industrial case. Also, Digital Twin as a Service (DTaaS) paradigm utilized for the digital transformation of unique wetlands with considerable advantages, including smart scheduled maintenance, real-time monitoring, remote controlling, and predicting functionalities. The findings indicate that there is a significant relationship between Digital Twin capabilities as a service and mass individualization.

1. Introduction

In light of the increasingly global competitive market, businesses must build data-oriented interactions to meet individualization [1,2]. The Fourth Industrial Revolution (Industry 4.0) holds the promise of increased flexibility, better quality, and improved productivity as an area of interest in digital transformation, from manufacturing to service and operations [3]. Nevertheless, the issue of meeting tailor-made features has received considerable critical attention [4]. Despite Industry 4.0 s' success, the individualization paradigm has several problems in practice [5]. Therefore, offering unique features at scale is one of the most wanted capabilities in the era of Industry 4.0 [6].

Unleashing Industry 4.0 capabilities require every physical asset, a digital representative [7]. Mirroring digital representative of physical assets can bring significant value to solve complex business challenges [8]. Besides, due to the lack of convergence between physical and cyberspace, the data is stagnant in the product lifecycle, which leads to a low level of efficiency and sustainability [9]. Advanced engineering and related Industry 4.0 technologies are changing the way engineers interact with physical assets by using represented digital data in an ever-increasing digital world. This study proposes Digital Twin as a Service (DTaaS) under Industry 4.0.

Digital Twin is under continuous development, which, by design, can distinguish assets. Recently, researchers have shown an increased interest in Digital Twin, but there is a relative lack of research focusing on Digital Twin for different paradigms, including massive unique assets. There is an urgent need to address interaction among the physical, digital, and human world caused by unprecedented global challenges. To date, DTaaS has not been empirically investigated. Therefore, it is becoming challenging to ignore the investigation of a holistic reference architecture for utilizing Digital Twin under Industry 4.0 umbrella.

This study employed secondary data, with data gathered from Scopus, Google Scholar, and Science Direct databases with the keyword "Digital Twin as a Service" in the abstract, title, and keywords search among academic journals, articles, and books since 2010. Besides, Digital Twin related review papers have investigated regarding a Digital Twin reference architecture model. This paper is structured as follows. After the introduction, section 2 provides the literature on Industry 4.0, reference model and architecture, Digital Twin, and individualization. Section 3 debates Digital Twin enabling technologies and a conceptual model. Section 4 proposes a Digital Twin reference architecture model in Industry 4.0 as the main contribution of this study. Section 5 outlines

* Corresponding author.
E-mail address: shohin.aheleroff@auckland.ac.nz (S. Aheleroff).

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how Digital Twin enables monitoring, controlling, and schedule maintenance for wetlands as a representative for a massive number of unique and dynamic physical assets. Section 6 concludes and point out future works.

2. Literature review

Digital technology has evolved to the point where advancements in the Industry 4.0 era move beyond constant and one-tier situation. There are limited studies related to how Digital Twin can manage substantial amount of different assets. This section reveals a literature review of Digital Twin, Industry 4.0, and individualization to cover the current and past related studies.

Digital Twin has been the subject of many classic studies for enhancing performance and reducing operating costs in assets, machines, processes, and specific application with different integration levels. There is a question that some frameworks and architecture are being developed for explicit Digital Twin purposes. Along with this growth in using Digital Twin for a wide range of industries, and applications, however, there is increasing concern over a suitable reference model.

The research to date has directed to Digital Twin technology rather than Digital Twin as a service for a great variety of industries and applications. Most studies in the field of Digital Twin have only focused on the manufacturing industry and related case studies to validate its design architecture. This investigation seeks to address research gaps by introducing pioneering DTaaS through an architecture reference model, demonstrating one of the most complicated situations.

2.1. Industry 4.0

Industry 4.0 empowers digital transformation and provides on-demand services with high reliability, scalability, and availability in a distributed environment. Industry 4.0 aims to revolutionize how products are manufactured to form the smart factories of the future towards higher creativity, lower cost, and better responses to needs [10].

Industry 4.0 systems, including Digital Twin need digitized knowledge [11] to present smart features and scaling up and down per demand through service-oriented and distributed resources [12]. A computable virtual abstraction of a real phenomenon is needed to functionalize cyber-physical systems under Industry 4.0 umbrella [13].

Industry 4.0 puts forward a value proposition where higher customer satisfaction can be achieved as manufacturing systems have become smarter by using IoT, cyber-physical systems (CPS), Cloud Computing, and Big Data [14]. Industry 4.0 converges advanced features allowing smart products and systems to provide competitive advantages. However, when a business study Industry 4.0 capabilities, the related architecture, and processes must also be adapted [15]. To this end, the development in the Industry 4.0 era is an integrated process of complexity and agility between humans and machines. At the same time, a unified architecture is required for reducing various complexity challenges [16].

3. Reference model and architecture

A reference model is an abstract framework representing components in schematic form in a simplified way. Following a review of the manufacturing sector, Tao et al. [17] conclude that there is an urgent need to define a unified Digital Twin framework. Yuqian et al. [18] introduced a Digital Twin reference model consisting of three crucial elements: Physical Objects, Communication, and Digital Twin consist of an information model to represent physical specifications and a data processing module to construct the live representation of a physical object. Alam et al. [19] shared an analytical description of a Digital Twin Architecture Reference Model, where peer-to-peer connections can be established between a physical and its digital representative in CPS. Helu et al. [20] introduced a reference architecture to integrate heterogeneous manufacturing systems for the digital thread with the ability to diagnose root causes and control of design and manufacturing in digital space. Bevilacqua et al. [21] kept users out of physical space and proposed a Digital Twin reference model for risk reduction in process plants. Recently, Shao and Helu from the National Institute of Standards and Technology [22] outlined an overview of the Digital Twin concept for individualization to create fit-for-purpose in the manufacturing industry. ISO 23247–2 series is under development for providing the overall structure of the domains and the entities of Digital Twin manufacturing reference architecture.

3.1. Digital Twin

A Digital Twin is a digital replica of a physical entity with the two-way dynamic mapping between a physical object and its digital model [23], which has a structure of connected elements and *meta*-information. ISO 23,247 series [22] defines a framework for Digital Twin manufacturing as virtual representations of physical manufacturing elements such as personnel, products, assets, and process definitions. NIST distinct, “The digital twin is a digital simulator or digital replica of a real IEEE 1451 smart sensor” [24]. Verl et al. notified that data-driven Digital Twin arises since Industry 4.0 capabilities have developed [25]. The digitalization of manufacturing processes needs to the reconfiguration of physical infrastructure for individualization [26]. According to the Centre for Digital Built Britain (CDBB), a Digital Twin is “a realistic digital representation of assets, processes or systems in the built or natural environment.” [27].

Digital Twin and Digital Thread are every so often understood to be synonymous. The Digital Thread covers a Product or System Development Lifecycle (SDLC), from its design, engineering, and creation to after operations and provide insight in better predictions and decision making [28]. Although both Digital Twin and simulation can execute replications in cyberspace, they are not the same as Digital Twin relies on real-time data from its physical counterpart and simulation is based on the study of mathematical models [29]. Other similar emerging concepts are Digital Cloning and Digital Immortality that both utilized AI to create hyper-realistic in more durable media [30].

Fig. 1 shows an adopted long-standing “Human, Process, Technology” framework for business transformation. Good relationships and balance among the three would lead to the highest organizational efficiency. As a term, Digital Clone represents human in digital space as an avatar, Digital Thread characterizes process, and Digital Twin symbolizes technology (3D-TCT) refers to the balance for a complex organization delivering value in an ultimate digital-oriented organization. This proposed framework breaks a system into components, showing how a fully digital system should work to support humans for achieving scalability, autonomy, and innovation.

3.2. Individualization

We have entered an era of individualization at scale. Nevertheless, developments in Industry 4.0 addressing challenges such as supporting the dynamic configuration [31]. By moving beyond mass production, companies face uncertainty and complexity caused by a wide variety of circumstances. To overcome the gaps, Wang et al. [32] proposed a framework in Industry 4.0 discussed suitable technologies, including IoT, Big Data, and radio RFID-enabled systems.

Mass customization and mass individualization are often thought to be synonymous. Customization [33] approaches are established based on the product family, whereas predefined products [34] do not well support the nature of individualization [35]. Mass individualization faces several challenges due to the absence of seamless integration of Industry 4.0 capabilities.

The ability to provision at low cost and short lead-time is a severe constraint in individualization, while the goal is to achieve efficacy near

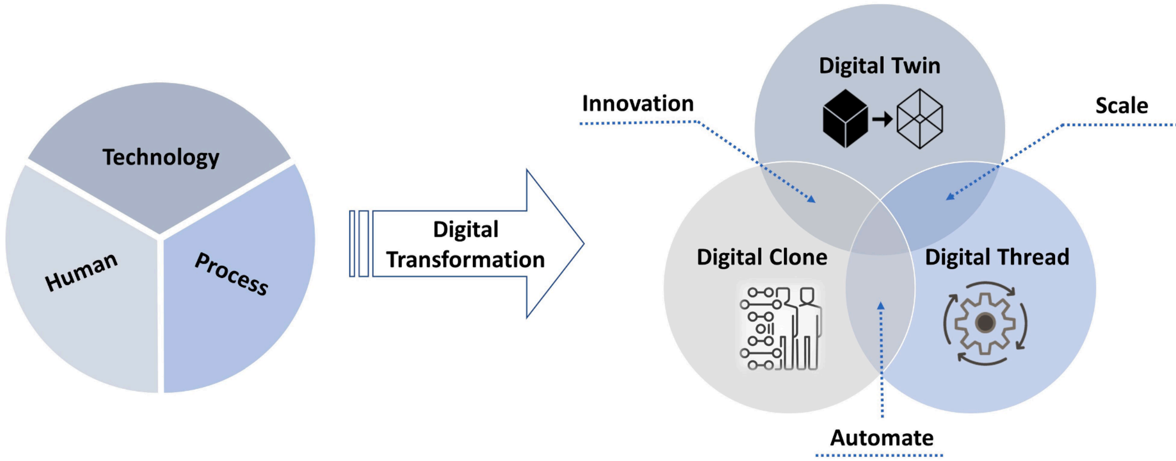

Fig. 1. Digital Transformation in Human, Process, and Technology.

to mass production [36]. Dependencies, changes, efficiency, and complexity are known as significant challenges in individualization [37]. Ambitious toward individualization could be compromised since the manufacturing industry needs to consider the paradox of green environment and growing demands [38,39].

4. A Digital Twin reference model

4.1. Digital Twin-enabling technologies

In today's connected world, data is the driver for a better understanding of real-time interactions. Planning and making decisions without the instant status of physical context can lead to potential risks. Digital Twin is characterized by rapid development with the ability to make exclusive changes to and from a digital representation of a real thing. Digital Twin can utilize essential Industry 4.0 capabilities with features, including instant feedback and predictions.

Fig. 2 illustrates that the Digital Twin is the next wave in modeling and simulation since the early simulation was limited to unique applications. The following simulation wave introduced standard tools for specific design and engineering topics. Multi-level simulation systems were the latest revolution before the emerging Digital Twin concept in the Industry 4.0 era [40]. Also, Digital Twin can be developed by using a simulation component and model component to mirror images of real-world in cyberspace [41].

Digital Twin in Industry 4.0 has received increased attention across several disciplines in recent years as Digital Twin can present enough precision for making a digital replica of physical appearances, functionalities, characteristics, processes, and systems. Digital Twin can distinguish preferences making it more suitable for better insights on individualization in operations, performance, prediction, and decision making. Digital Twin changes the traditional approach of the first build and then tweak in the Industrial 4.0 era.

Fig. 3 proposes crucial Industry 4.0 technologies altogether, including IoT, Cloud, Extended Reality (XR) [42], Big Data, and Machine Learning (ML), with the ability to learn and advance through aggregating, analyzing, visualizing, and predicting as the significant features in Digital Twin. First, digital models of needed and wanted physical assets presented in cyberspace using Cloud technology. Secondly, building instant communication between digital and physical counterparts with IoT. Thirdly, Digital Twin under Industry 4.0 can expand the volume and variety by consuming Big Data and learning from the data. Fourthly offers better visibility and insight into the entire product and service life cycle by employing ML to identify patterns and make on-time decisions. Finally, yet importantly, the full fidelity of a Digital Twin would be feasible via XR in three 'P's' – Products, Processes, and People. XR is representing Augmented Reality (AR), Mixed Reality (MR) and Virtual Reality (VR). These core Industry 4.0 technologies have integrated for building a backbone to close the gap between digital and physical by providing instant access to digital models that virtually represent their physical complements.

4.2. A conceptual Digital Twin reference model

While almost all studies are using the same concept, there is a need to make sure a Digital Twin model can be used as a reference by a wide range of applications and paradigms from mass production to mass individualization. Digital Twin is not limited to manufacturing due to its

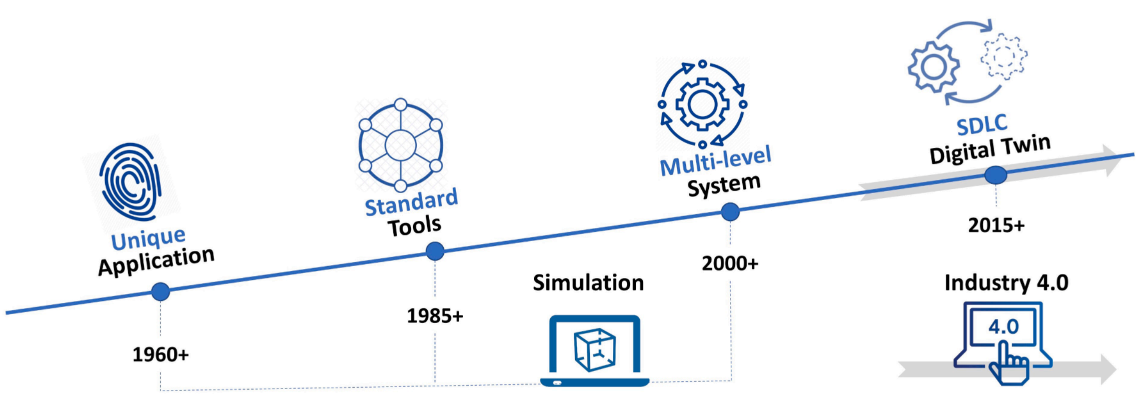

Fig. 2. The Path Toward Digital Twin.

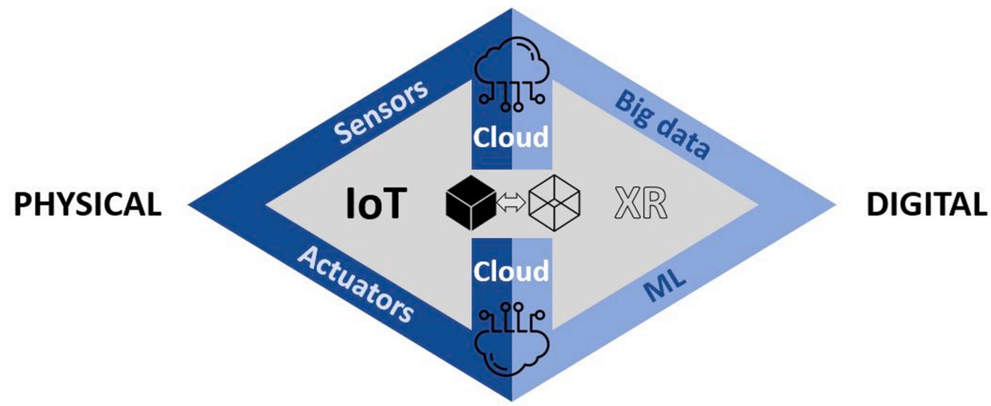

Fig. 3. Crucial Industry 4.0 Technologies for enabling DTaaS.

prominent industrial cases in providing a digital replica of potential physical assets, devices, processes, systems, people, and places [43]. In the industrial context, a physical thing is born as a digital model that may not be created without CAD/CAM models. Digital and cyber are every so often understood to be the same while missing one may not suit a reference model. Fig. 4 illustrates a Digital Twin reference model consists of four parts: Physical layer, Digital layer, Cyber layer, and communication for data exchange among the three layers, which carry real-time data as a mapping between selected physical elements and their digital model and process in cyberspace.

The physical layer defines the means of real attributes, including resources such as objects, assets, products, personnel, equipment, facilities, systems, processes, environment, or Thing that has material existence in the physical world. Sensors and actuators are the two main connected things in the physical layer. The former senses a physical condition or chemical compound and delivers an electronic signal to the detected and measured characteristic. The latter is a component responsible for moving and controlling a mechanism to achieve a task, for example, by turning a smart pump on or opening a smart valve over the Internet.

The digital layer is the recording of data in raw or different file formats such as Computer-aided design (CAD) or Computer-Aided Manufacturing (CAM) to support the creation, modification, analysis, optimization, or prediction of a static, dynamic, and real-time data. Often digital models are designed in a storage medium before creating physical assets. The digital layer is dedicated to just enough item creation of physical things. This layer hosts designed and developed files to represent needed, wanted, and expected outcomes in the physical layer. A bidirectional link makes the concept of modelling and simulation possible.

The cyber layer includes Cloud processing and storage for building a dynamic data model, which can enable digital capabilities at scale. Also, the data model builds information, knowledge, and wisdom (DIKW) by using IoT, Big Data, and Cloud technologies for a wide range of Digital Twin enabled applications, including diagnostics and prognostics [44].

The cyberspace layer brings significant value beyond modelling and simulation for mass production. Cyberspace has emerged as a powerful interconnected digital technology with the ability to achieve the most complex manufacturing paradigms due to the advanced features associated with CMfg, Big Data, IoT, ML, and Blockchain. The cybers layer adds several competitive advantages, including data privacy, transparency, scalability, and individualization, in comparison with the digital layer.

For instance, the counts of COVID-19 cases have passed five million at the time of this writing. Factory workers exposed to the virus, and consequently, manufacturers are facing challenges with the pandemic, which several went collapsed. Critical workers need permission to ensure continuity of operations of essential functions. Thus, there is a need that workers wearing a mask have a good fit since everyone has different face shapes and sizes. The steps are as follows:

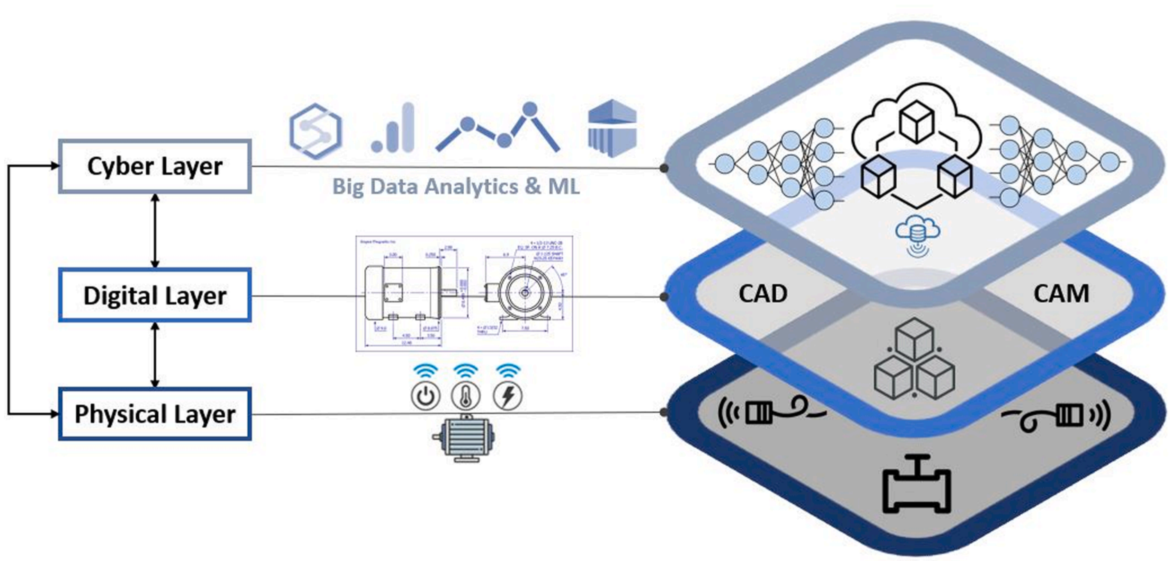

Fig. 4. A Conceptual Digital Twin Reference Model.

1. Develop CAD files for predefined (Small, Medium, Large, Male, Female) masks.
2. Face recognition by using a Kinect camera or smartphone with a 3D camera.
3. Adjust a predefined CAD file based on the most suitable family product.
4. Manufacturing by using a 3D silicon printer based on the modified CAD file.
5. Offer insight using Big Data and ML based on the real-time data.
6. Personalize a CAD file to achieve the most comfortable and sealed mask.

In the digital layer, CAD files are created to represent what a customized physical mask will be like. Second, the cyber layer powers by massive amounts of real-time data enriching to information toward knowledge about individual masks. Unlike the digital layer, the cyber layer keeps track of historical data for other analytics to scale up regardless of the variety of masks. A one-to-one connection between every designated mask makes this reference model suitable for mass personalization, which develops gradually through the bidirectional communication between physical and cyber layers.

This reference model contributes to advance the understanding of Digital Twin capabilities and address the growing area of research in similar global challenges. In recent years, different Digital Twin reference models have been proposed to investigate the role of digital and cyberspace. This reference model is particularly useful in practical studies with the benefits of both digital and cyber layers. The second advantage of this model is beyond Digital Twin monitoring and controlling toward continuous improvement and predictions. Last but not least, individualization is more feasible as the most tailored product can be designed in the digital layer for final manufacturing.

5. A Digital Twin reference architecture model in Industry 4.0

Digital Twin can bring significant value to digitalization as a principal element of industrial resilience and sustainability. Industry 4.0 is the ongoing transformation of traditional industrial practices integrated with the cutting-edge technologies aimed at added value from the data flow. Given increasing importance and impact in the Industry 4.0 era, the Reference Architecture Model for Industry 4.0 (RAMI 4.0) was developed by the German Electrical and Electronic Manufacturers' Association to support Industry 4.0 initiatives based on a holistic view of manufacturing enterprises. RAMI 4.0 gives businesses a holistic framework for developing future products and business models using a three-dimensional map in a structured manner complemented by the Industry 4.0 components [45].

Architecture is mostly defined as a system and relationships to address the fundamental structure of elements, relationships, interfaces, processes, restrictions, principles, purposes, physical, and logical properties [46]. RAMI 4.0 brings a common understanding of digitized industrial use cases involving the design, development, and deployment, which can be adopted as a model for almost all Industry 4.0 applications similar to the seven-layer ISO/OSI model, which is used as a reference for network protocols. The advantage of using such models is a shared understanding of a model. Furthermore, RAMI 4.0 defines a service-oriented architecture (SOA) that provides different services.

The basic principles of SOA are independent of vendors and products [47]. Finally, RAMI 4.0 can help break down complicated work into simple structured packages align with crucial aspects of Industry 4.0 capabilities. Fig. 5 shows a Digital Twin reference architecture model in Industry 4.0. This 3D layered model comprises of three dimensions coordinate arrangement that describes all crucial aspects of Digital Twin. In this way, complex interrelations are broken down into smaller and simpler clusters, including five Digital Twin layers, agile value life cycle [48], and Digital Twin integration hierarchy [49].

The value of the DIKW model has been used in many domains for representing a structural relationship between data, information, knowledge, and wisdom. The proposed model offers a DIKW matrix with the dimension of the left axis and the right axis. Moving from the physical layer, the bottom layer to the top, the application layer represents the DIKW hierarchy as collected data by smart sensors, and IoT enriches to information and knowledge by using Big Data on the cyber layer and presented as a pearl of wisdom in the application layer. However, like many other models, DIKW has its limits due to linear consequence of stages with knowledge being a progression of data and information.

Unlike the DIKW model, the proposed Digital Twin reference architecture may bypass the DIKW steps if required. The physical layer in this reference model uses can capture unstructured data through smart sensors and IoT. Also, by using Big Data, and Cloud computing technologies over the cyber layer can achieve smartness, self-learning, and autonomy capabilities for making instant actions without following the DIKW structured hierarchy. For instance, in the case study section, the proposed DTaaS model used an application programming interface (API) to bypass the DIKW hierarchy and integrate the outcome DTaaS for predictive maintenance.

The other advantage of this reference model is the knowledge model based on the relationship between the left axis, the Digital Twin layer and the right layer, the level of Digital Twin integration. The four-level of Digital Twin integration represents the four-level in the DIKW

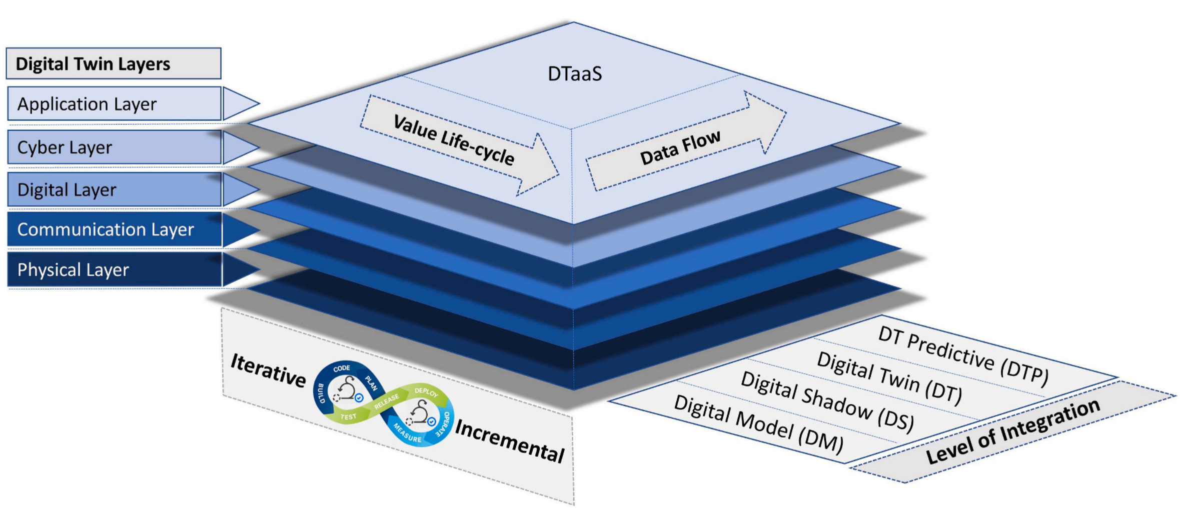

Fig. 5. A Digital Twin Reference Architecture Model in Industry 4.0.

hierarchy. The data flow shows the Digital Twin predictive in this Digital twin reference model is where wisdom is placed on top of the DIKW model.

5.1. Digital Twin Layers, the vertical axis

This subsection discusses the left axis shown in Fig. 5. The vertical axis describes the five Digital Twin layers comprising an interlinked set of physical, communication, digital, cyber, and application layers. This reference model can develop from simple to the most complex Digital Twin enabled applications. Cyber layer interconnected digital technology over the Internet, and they are not synonymous terms. The difference comes in how we perceive each; The digital layer has to do with an imitated digital copy of physical things, including geometric data and can exist in digital form on various electronic, magnetic, or optical disks while the cyber layer is using scalable and distributed computing technologies such as AWS, Azure Databricks, Hadoop, and Google Analytics. The cyber layer is in the effect of Big Data, algorithms, and DL technology for advanced applications, including risk management, optimization, and predictive analytics.

Fig. 6 illustrates that the Digital Twin layers in the proposed reference architecture model are to align with the 5D product design process. The five "D" s stand for "Define, Design, Develop, Discover, and Deploy." In the "Define" phase, a solution for a physical/ real problem, need, or want will be conducted. "Design" and "Development" are participatory phases in the Digital layer to make the digital version of products, services, and processes that mostly resulted in CAD and CAM file format for meeting the expectations in the real world. Big Data enables us to gather data from the physical layer to start delivering personalization. Consequently, cyberspace empowers rolling products and services concerning adjustments, revision, improvements, predictions, UX/CX design, and individualization through an iterative, incremental process. "Discover" phase linked with the "Define" phase via the Communication layer to make the outcomes available in the Application layer as a Digital Twin enabled user interface. We turned the 5D methodology, line up with iterative, incremental value lifecycle in the middle axis.

5.2. Level of integration

This subsection discusses the right axis shown in Fig. 5. There are different kinds of digital twins due to personalized technique for capturing the dynamics of the underlying circumstance [50]. The four layers on the right axis characterize the different Digital Twin integration levels. Such representations originate by Kritzinger at al. [49] from a categorical literature review of the Digital Twin in manufacturing and existing publication. The Digital Twin is commonly known as a key enabler for the digital transformation for a different level of integration. The terms Digital Model, Digital Shadow, and Digital Twin are often used synonymously, while data integration toward the physical, the digital, and the cyber layers are not the same. Fig. 7 shows a 'Digital Model', which does not have a real-time link to and from a physical thing like simulation and mathematical models. If a change in the state of a thing leads to an instant change of state in the digital things, then the one-way real-time data communication from physical to digital space makes a 'Digital Shadow', a significant application in real-time monitoring. A bi-directional real-time data communication between physical and digital space builds a twin. A 'Digital Twin' integration emerges Digital Twin enabled applications in production planning and control [51], maintenance [52], and layout planning [53]. However, the ultimate goal is beyond Digital Twin integration to achieve further analysis for predictions [54] and individualization by using Big Data and ML in cyberspace. 'Digital Twin Predictive' (DT_p) is a digital replica of a physical thing, which uses a two-dimensional real-time data communication over cyberspace.

5.3. Value lifecycle

This subsection discusses the middle axis shown in Fig. 5. The left horizontal axis represents an iterative, incremental product, and service value lifecycle. Changing characterizes digital Twin, and agile working is a proactive response. Digital Twin has the features, including data-oriented individualization, to build on self-directed, continuous improvement by using Agile methodology.

While RAMI 4.0 suggests the life cycle of products and services through a linear sequential phase, this model supports the power of communication, digital, cyber, and application layers on the vertical axis through iterative, incremental approach for better monitoring, controlling, and predicting. Every Digital Twin layer on the left axis, in conjunction with the appropriate level of Digital Twin integration on the right axis, can be joined through the iteration of continuous development. Therefore, this iterative, incremental value life cycle complies with the five Digital Twin layers on the vertical axis and Digital Twin integrations on the right axis.

The Agile Digital Twin value life cycle creates a replica of the physical world by using ready-to-use data for incremental development, which describes things as they are now. All Digital Twin integration levels, regardless of the offline or real-time data link between a real thing and its digital replica, could be developed in an Agile process.

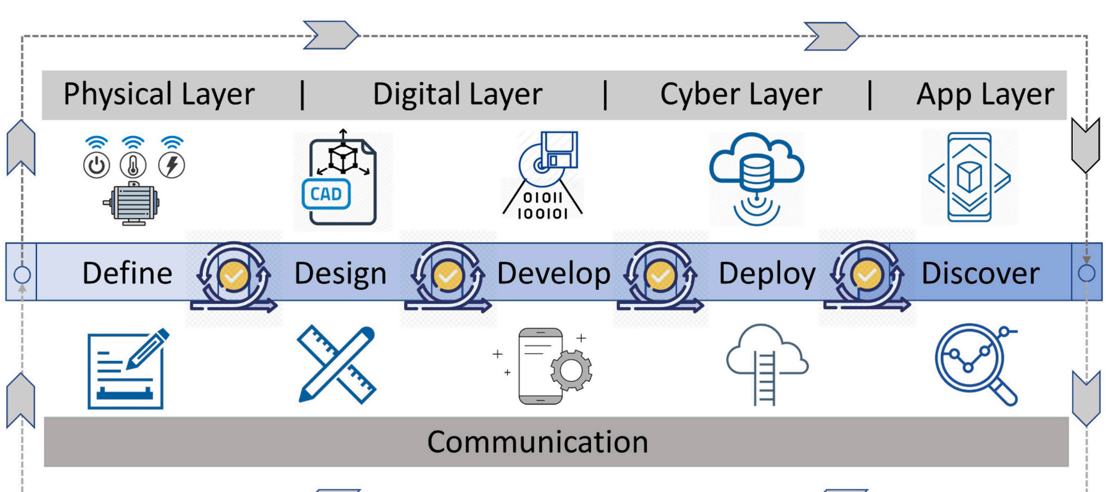

Fig. 6. Digital Twin Layers in the Proposed Reference Architecture Model.

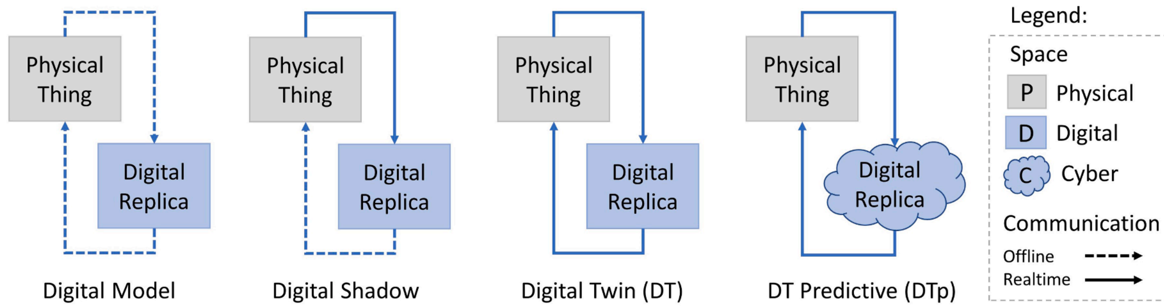

Fig. 7. Digital Twin Integration Levels in the Proposed Reference Architecture Model.

Besides, Agile value lifecycle can predict the future by comparing past scenarios and seeing how the twin responds with minimum wasteful trial-and-error. Therefore, the value lifecycle axis plays a considerable role in this reference model due to the similarity between Agile and Twinning concepts as both are suitable for individualization.

Fig. 8 shows that Digital Twin involved in consequence of requirement gathering, functionality & appearance requirement analysis, Digital Twin-enabled monitoring, controlling, test, and Additive Manufacturing through an iterative, incremental process [55]. This Agile methodology can provision mass individualization under Industry 4.0 umbrella. IoT, Big Data, and DL allow customers to create a Cloud-enabled Customer Profile (CCP) by capturing preferences through real-time interaction between physical, including smart products and services and cyberspace. The result represents customer backlog, a live wish list of functionalities and appearance, reflecting all the requirements. Then, product backlog will be selected based on a priority. For instance, a customer would be able to make a diverse set of changes in the color and shape of a facial mask. The performance can be visualized by following continuous feedback for improvement.

5.4. *Digital Twin as a service (DTaaS) in Industry 4.0*

We are living in the digital era, and the trend for individualization has been moving beyond digital modeling, simulation, and digital twinning since Industry 4.0 emerged. A "phyber," (physical plus cyber) refers to blending online digital experiences with physical ones over cyberspace satisfying user experience. A "phyber," indicates a blended concept with DNA mutually involving in physical and cyberspace. A phyber has joint life in physical and cyberspace, which can grow in an iterative, incremental process using its digital origin. Therefore, individualization increasingly becomes phyber by taking the best aspects from physical, digital, and cyberspace.

By design, Digital Twin bridges the gap between design and deployment due to the mirroring capability of the real and cyberspace, which bring visibility and interaction for describing the SOA paradigm. Visibility refers to the capacity to see each other. Interaction is the activity of using a capability. This model promises a correlation between needs and capabilities from fundamental to complex [56]. This reference model representing Digital Twin as a Service "DTaaS" within the three-axis supporting all crucial aspects of Digital Twin combines the following related ideas:

- o The capability to perform work for phyber.
- o The specification of the work offered for phyber.
- o The offer to perform work for phyber.

The role of DTaaS is to offer capabilities and act as a service provider. Any phyber with needs that make use of services are referred to as Digital Twin-enabled service consumers. This reference model is an abstract framework for understanding relationships among the three-axis consists of unifying concepts and relationships altogether across physical, digital, and cyber domains for providing shows that DTaaS. The main drivers for this reference architectures are facilitating the manageable growth of large-scale Digital Twin systems, facilitating provisioning on cyberspace, and efficient use of resources using different integration levels through an Agile lifecycle. The value of DTaaS is providing a simple, scalable paradigm to realize the importance of mass individualization. Indeed, DTaaS is scalable because it makes the on

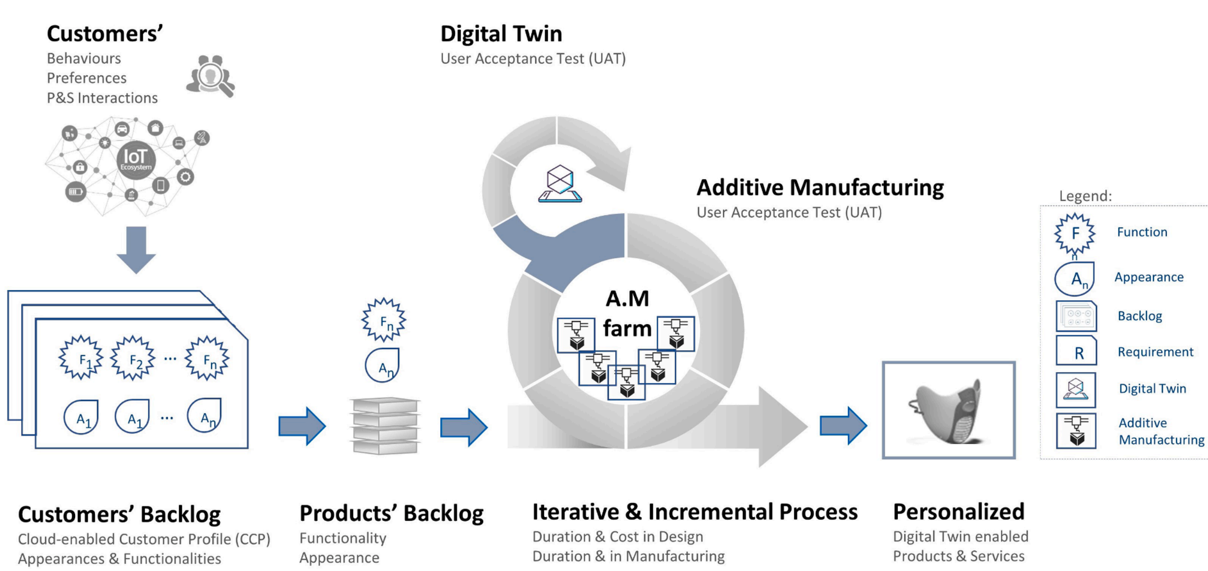

Fig. 8. Agile Value Life-Cycle in the Proposed Reference Architecture Model.

cyberspace.

Fig. 9 illustrates the principal concepts this reference model defines. DTaaS is a service to enable access to Digital Twin capabilities, where the access to phyber is provided using augmented interface across physical, digital, and cyberspace. Like any consumer/provider relationship, DTaaS, and consumers need to interact with each other using the communication in vertical axis. Interacting with DTaaS interacts performing actions by sending and receiving data using IoT. However, this can be referred to as message exchange as the primary mode of interaction with a service. The information model of DTaaS is a characterization of the data exchanged and often used by ML through DT_p integration with the service. DTaaS can be implemented with web services such as REST, COBRA, Apache River, and SOAP, to build an integration among IoT, AR, Cloud, and Analytics which makes the service accessible over standard internet protocols.

5.5. Advantages and discussion

The main benefits of this proposed Digital Twin reference architecture are as follows:

- The model integrates different perspectives and provides a holistic way of seeing the full potential of Digital Twin capabilities under Industry 4.0 umbrella.
- Requirements of different manufacturing paradigms can be addressed from mass production to mass customization and mass personalization.
- This model offers a map for Digital Twin enabled solutions to plot the requirements of development in each Digital Twin layer, together with the right integration.
- This reference model can help break down a substantial challenge into smaller that can be understood, tackled, and refined according to the vertical axis.
- This model integrates the relationships between different levels across the left and right axis and shows iterative and incremental progress through the middle axis.
- There is an inspirational interest with Digital Twin initiatives to work cooperatively and overcome the different interpretations, reference models.

The invasion of Industry 4.0 is starting to improve almost all industries toward more productivity, efficiency, flexibility, agility, profitability, and individualization. However, to do this effectively takes further case study development, and it is challenging for the proposed reference architecture model as a principal point for understanding the entire digital transformation.

5.5.1. DTaaS for future workforce and humans

Digital Twin as an enabling technology can be more precise than humans due to more efficiently at a consistent level of accuracy (the right axis in Fig. 5) and instance response (communication level in the left axis in Fig. 5) between physical and digital replicas. This DTaaS can drive radical changes to minimize human errors, perform at higher levels of competence, and optimize different aspects of processes in industries, including manufacturing, agriculture, construction, engineering, and transport to collaborate with humans. The proposed DTaaS makes triple integration among humans, cyberspace, and physical world [56] and gives rise to smart systems with autonomy due to the seamless integration of crucial Industry 4.0 technologies.

The right axis in Fig. 5 shows the different integration level between digital space and physical world to act the best decision when required. The proposed Digital Twin reference model is aligned with the emerging industrial transformation, where all the elements and their digital replica can have decentralized interactions for future-proofing attributes of the workforce [57]. Therefore, DTaaS enables moving from a physical pyramid-based communication to heterogeneous social network in Industry 4.0 regardless of physical constraints and number of individuals.

5.5.2. DIKW in the proposed Digital Twin reference model

Like the 5-level CPS architecture [56] the very first objective of the proposed Digital Twin reference model is to collect data from assets in the physical layer of the vertical axis by using IoT. Digitized knowledge to function is required [41]; therefore, the digital data reach the ultimate stage, where wisdom is given to users at the application layer in the form of augmented user experience. Therefore, a Digital Twin enabled model under Industry 4.0, which relies on IoT, Cloud, and Big Data to convert data to information, knowledge and wisdom. However, this model has driven the bottom layer of the DIKW, hierarchical model, with data at its base. This Digital Twin model is data-oriented, emphasizing seamless integration by enabling Big Data analytics to explain capabilities, such as the predicting risk of failure for the best possible action like knowledge-oriented, decision-oriented, and system-oriented frameworks.

The left axis in Fig. 5 explains the data exchange among digital-physical integrations. The collected data from the digital and physical interactions over time can be used by Big Data to build knowledge for prediction, act the best, and prepare for adaptation as a best practice. Therefore, DTaaS enables transforming data based on the DIKW hierarchy and gives rise to heterogeneous systems everywhere with distinctive self-learning, self-optimization, autonomy, and adaptation features under industry 4.0 umbrella.

5.5.3. Semantic

Building Information Modeling (BIM) is a process that begins with the creation of an intelligent 3D model [58], gives the insight to efficiently enable iterative and incremental development (Fig. 8) across the entire value lifecycle (Fig. 5, the middle axis). This DTaaS paradigm aims to enhance existing models with their supporting semantics within the context of Industry 4.0, where the digital models reflect the physical assets and vice versa at any given moment in time. As such, a review of existing building information modeling and their underlying semantics show that DTaaS concept fulfills the requirements.

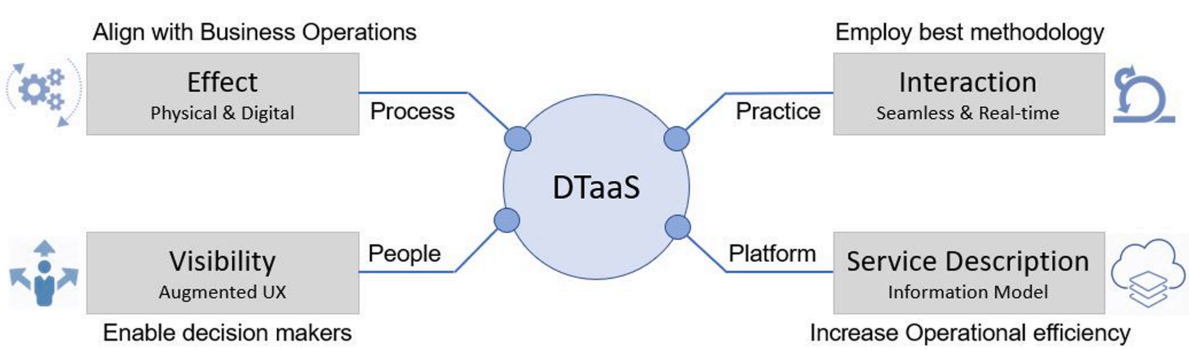

Fig. 9. Digital Twin as a Service (DTaaS) Capabilities.

Retrieving the semantic content of a considerable number of assets in different applications is still far from satisfactory. This Digital Twin model offers a vision of the future by moving from an off-the-shelf solution toward mass personalization. Adopting scalable and autonomous capabilities in Industry 4.0, along with the digital representation of unique physical assets, create an opportunity to address some challenges concerning semantics. This Digital Twin model is an effort to augment properties of distinctive assets, structure, product, and process regardless of size and complexity. The assumption behind this model is that the syntactic properties of digital things have reflected the physical characteristics.

5.5.4. Autonomy

With the evolution of Industry 4.0, a new trend of Digital Twin has emerged. Although cutting-edge technologies being applied to most smart applications, it is challenging to provide a digital replica of unique and dynamic physical asset at scale. This case study utilized an industrial IoT, an augmented reality software development kit, a Big Data analytics, and Cloud that enables DTaaS to offer an autonomous, augmented, and real-time service across very diverse constructed wetlands.

This model has a relatively high level of discretion granted to users with the capacity to make an uncoerced decision. Therefore, it offers autonomous capability because DTaaS can independently and instantly represent a digital replica of the physical asset in a dynamic environment without interfering with the additional facilities. As this proposed model utilizes Industry 4.0 technologies, mainly IoT, therefore, autonomy as an essential facet of Industry 4.0 is inherited. The case study in the next section explores the applications where DTaaS offers autonomous and real-time connectivity.

6. Case Study: Wetland schedule maintenance

Like most technologies, Digital Twin will only have a prolonged life when practical implementations and value-added products or services are seen. While Digital Twin adopted exclusive features such as ubiquitous and real-time connectivity from IoT, it has additional value propositions beyond digital modeling and simulations. The proposed Digital Twin reference architecture is enabling the development of new applications as a service across the entire value lifecycle to create interactions between people, smart devices, and wetlands.

There is a particular purpose associated with interacting with DTaaS. The primary service consumers, the city council and community members are using it to do the real-world effect of using the service. A wetland is the most biologically diverse of all ecosystems that play several essential functions. Constructed wetlands are large shallow planted ponds that filter stormwater runoff, slow flows as a buffer, carbon sink, help control flooding downstream, and recreation and tourism attraction. The nature of a constructed wetland is made-to-order; therefore, managing a vast number of wetlands with continuous changes is challenging.

DTaaS validated through a compelling R&D project for the maintenance schedule of constructed wetlands and describes how to utilizing IoT, AR, and Big Data technologies for building DTaaS, modeling a vast number of dynamic and unique environments, providing real-time 3D user experience, and prediction feature by using the proposed Digital Twin reference architecture model.

This study utilizes DTaaS to the maintenance schedule of more than five hundred unique wetlands in 2,400/km^2 urban density combine the flexibility in a custom-made environment in Auckland, New Zealand. DTaaS is used to learn about the key factors in every unique wetland, monitor, control, and ultimately predict real-world effects in schedule maintenance. The focus of this industry-led case is to understand better the influence of Digital Twin in a very complex and dynamic business challenge.

Fig. 10 shows how digital representatives of constructed wetlands across New Zealand are represented in cyberspace. DTaaS can turn wetlands into data-driven assets, which brings a competitive advantage to wetland schedule maintenance. Along with the growth in constructed wetlands, there is increasing concern over the operations of a significant number of custom-made wetlands. The expansion of constructed wetlands raised several challenges for a large company that operates distributed network branches throughout the country by supplying over 40,000 product types, consisting of drainage, water main, environmental, industrial process, and agricultural applications, which needs a full inspection and maintenance of wetlands before, during, and

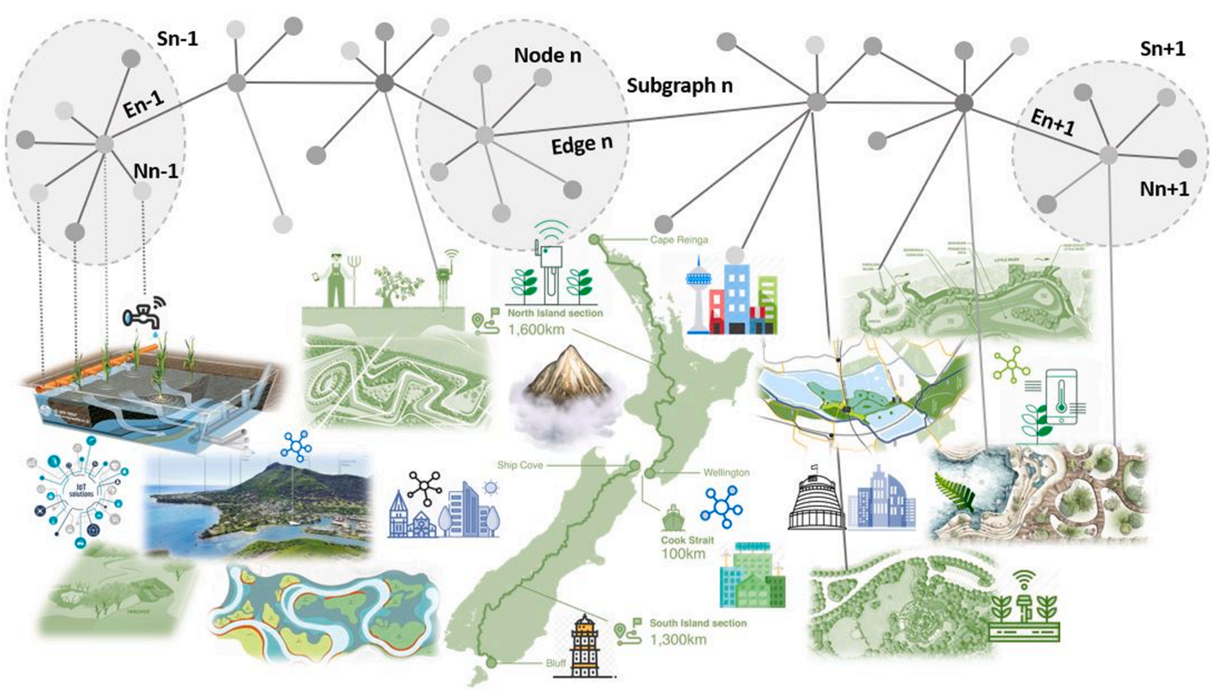

Fig. 10. DTaaS for Wetland Schedule Maintenance in New Zealand.

following storms. Firstly, wetlands should continue to function as designed for filtering stormwater, slowing flows, and controlling downstream flooding. Secondly, to offer a healthy and attractive landscape for ecologists and tourists to explore in the country.

A natural wetland is not represented by a single node, but by a subgraph of nodes and edges. For example, "Western Spring" wetland is characterized by multiple nodes and edges in a subgraph. The real-time data is collected from the field by smart devices, so nodes in the subgraph represent the wetland's CAD design, including inlet, sedimentation forebay, main wetland, shallow wetland area, plants, risers/ outlets, anti-seep collar, and emergency overflow data. Several smart connected sensors have placed for monitoring water level, water quality, and sediment along with actuators for controlling pumps and valves. Edges are connecting subgraphs to record transactions for predicting, controlling, and monitoring. The business challenges are as follows, while there is no early warning of pollution from upstream sites.

- o Fixed scheduling of maintenance.
- o Lack of real-time monitoring and controlling.
- o Lack of prioritization based on different factors.
- o Lack of a user-friendly channel for the community.

The next two sections show how the proposed Digital Twin architecture helps to develop BIM and solve these problems by replacing the current fixed plan after storms, monthly, six months, annually, and two years. Besides, this Digital Twin solution proposes the community to interact with individual wetlands through a real-time Digital Twin interface.

6.1. A Digital Twin architecture for the wetland schedule maintenance

Since data is at the center of the Digital Twin architecture concept, one must consider immediacy and depth of insight while presenting a digital version of physical assets. The faster the data needs to be transferred, the closer to the cyberspace for representing to be. Fig. 11 illustrates a Digital Twin architecture for smart wetlands comprising four primary Industry 4.0 technologies, including IoT, AR, Big Data, Cloud as proposed in subsection 3.1. Orchestration of these core technologies provides an interactive connection between physical and digital over cyberspace, as proposed in Fig. 4. This developed architecture adheres to a service-oriented architecture based on the proposed 3D layer Digital Twin reference architecture in Section 4.

The three-axis has shown in Fig. 5; the proposed Digital Twin Reference Architecture Model was adopted to build a Digital Twin for supporting significant wetlands. The middle axis has detailed in Fig. 8, where a more comprehensive range of assets was developed gradually through an incremental, iterative process. The detailed process is shown in Fig. 14 and described in subsection 5.3. Regarding the right axis, DTp as the highest level of integration has implemented where ThingWorx analytics and a weather API integrated for prediction. Regarding the five Digital Twin layers in the left axis, the physical layer consists of sensors and actuators in each wetland. ThingWorx represents communication, the 2nd layer. The Digital layer, the 3rd layer is the digital version of each unique wetland in the form of CAD files. The cyber layer, the 4th layer is where we use Vuforia for instant UI presentation and Big data analytics by using ThingWorx analytics. Besides, the integration of APIs, including whether and social media demonstrates SOA capability, which resulted in DTaaS for a vast number of unique wetlands regardless of location.

IoT collects data from a constructed wetland toward the sensor data in the cyber layer. The representation of the data is key to modeling a live wetland. The sensor data provides the current state of desire parameters and source predictive engine for prediction. Fig. 12 illustrates the awareness feature based on the three subsystems: Sensor Data, Predictive ThingWorx Analytics, and Real-Time Alert. While the data in each transaction is not significant, big data plays an essential role in the relationship between entities and continuous data growth for building digital models. The backend process configured to alert when the water level exceeds a threshold.

Every real Thing in a wetland and its corresponding in Digital Twin connect by IoT. For instance, Water Level ThingShape is a digital ID for the water level in a constructed wetland. IoT allows push/pull data to and from Digital Twin and permits a bi-directional dataflow to create a virtual representation that matches the physical attributes of a "real world" in real-time. Therefore, Digital Twin does not stand alone because it must be integrated with the overall IoT and Cloud architecture. The proposed architecture achieved through the convergence of core Industry 4.0 capabilities, together with AR, Cloud, big data, and IoT

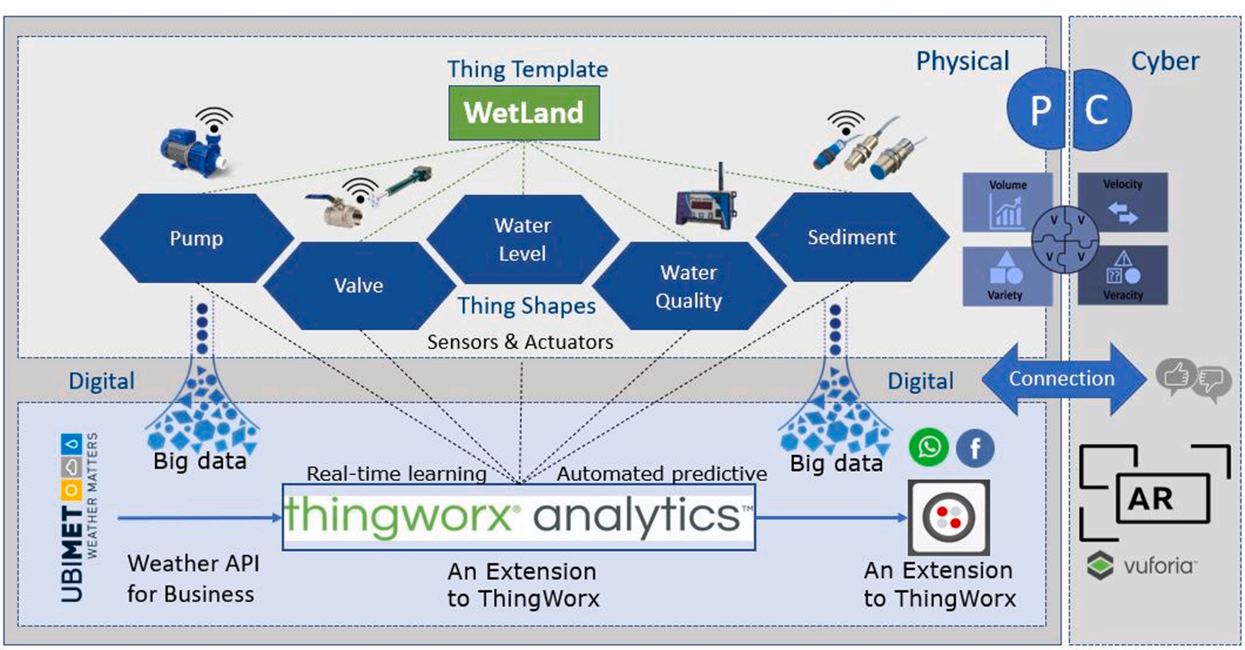

Fig. 11. Digital Twin Architecture for Smart Wetlands using ThingWorx & Vuforia.

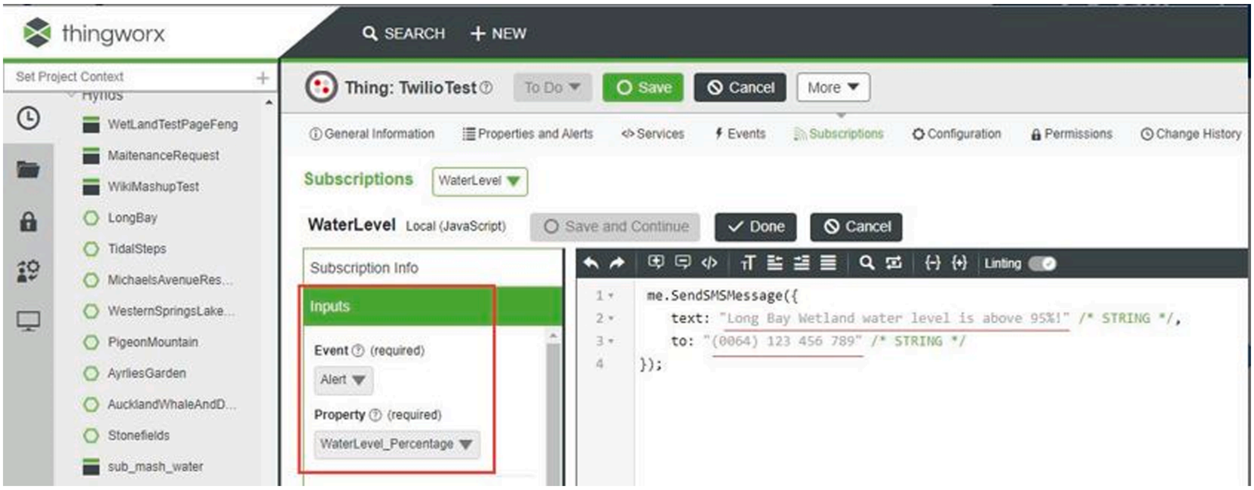

Fig. 12. Digital Twin-enabled Real-Time Alert in a Backend Process.

technologies. This Digital Twin architecture fulfills a massive number of individual physical assets, making it a suitable architecture for mass personalization under Industry 4.0 umbrella.

6.2. IoT-enabled Dashboard

Digital Twin of a wetland is a virtual model of smart infrastructure, not only in the design plan but also in operations. IoT makes digital replicas far more useful, cost-effective, and real-time data from wetlands. IoT integrates the natural wetland with its digital assets in cyberspace. IoT enables data to flow from smart devices to a developed Digital Twin system and offers data-driven visibility into the lifecycle, operational intelligence, and optimizes maintenance of wetlands.

This section demonstrates how a constructed wetland transformed by a convergence of IoT for collecting real-time data from individual sensors and smart devices in a wetland. Fig. 13 illustrates a mashup in ThingWorx, an Industrial IoT platform, containing a map, gadgets, a data list, remote control, and security extensions. This IoT-enabled system offers eight main features: real-time monitoring, prioritization, remote-controlling, visualizing historical data, outlining unique plants, overall and individual wetland's status, and wetlands' status indication the map, and backend community feedback processing.

Realtime data is streamed from wetlands to this IoT-enabled system. Based on collected data from smart sensors and the backend process, wetlands are graded in three states, "Critical," shown in red, "Warning," displayed in yellow, and "Healthy" shown in green. Digital representatives of a wetland are colored on the map based on the latest status, representing the dynamic situation of a selected wetland. Each wetland is listed in a table next to the map. Historical data of wetlands are kept for further investigation and analytics by using big data.

The schedule maintenance of wetlands is achieved based on the crucial factors, including water level and quality. While wetlands are uniquely constructed, their digital representative is dynamically segmented into three groups. For instance, if heavy rainfall is forecasted, wetlands can be sorted based on the latest water level to carry out urgent maintenance to address high flooding risks. This Digital Twin system enables monitoring and controlling capability through a connection between physical assets, valves, and pumps, and their digital representatives. Two-Way data flow between assets and their digital representative is an essential function of Digital Twin. Therefore, the digital representatives can act as directing wetlands. A change in the state of physical factors in a wetland leads to a change in digital representatives.

6.3. Digital Twin user interface

AR is one of the most superior technologies that allows users to see virtual objects overlaid in the real world. Rather than replacing reality, AR supplements instant data by using IoT for building unique Digital Twin experience. The value of real-time, 3D content and cumbersome processes for scaling and updating are critical factors for smart wetland

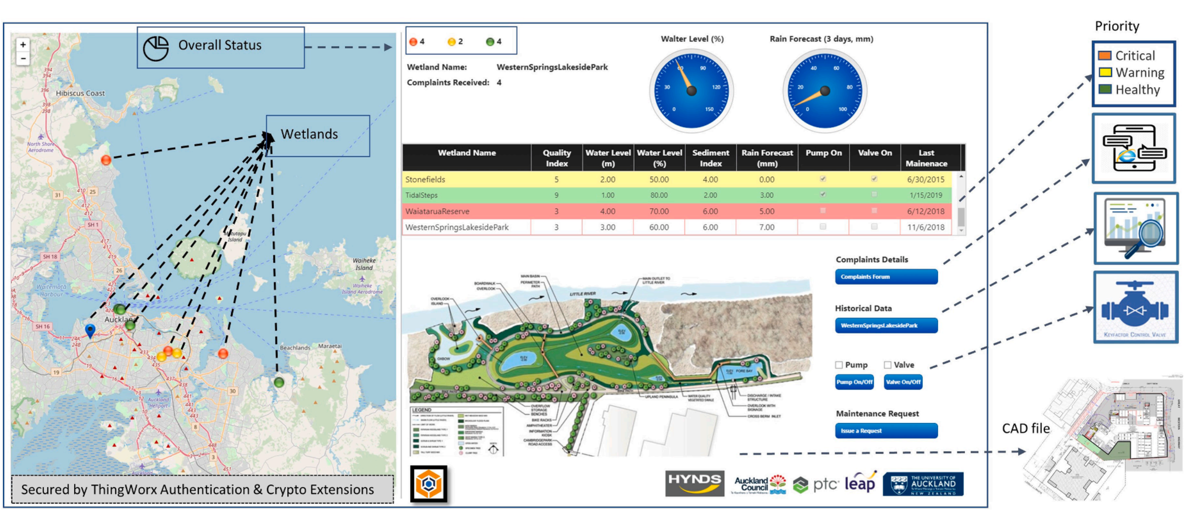

Fig. 13. A Digital Twin-enabled Dashboard for Controlling and Monitoring Wetlands.

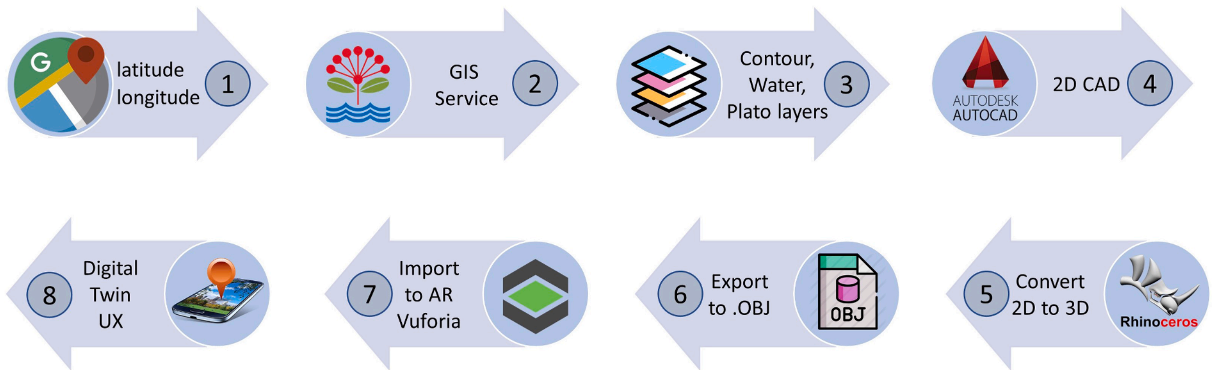

Fig. 14. Process for Building AR-enabled Model of Individual Assets.

maintenance systems.

Fig. 14 shows the eight steps for building the AR-enabled model of individual wetlands. For instance, the latitude and longitude of Western Springs (36.8619° S, 174.7183° E) wetland identified. The 2nd milestone is to use the public Auckland Council GeoMaps service, which contains spatial and non-spatial information from across Auckland. The 3rd step is to select plot boundaries, extract, and download necessary information, including countour, stormwater, and wastewater and submit the request. A 2D CAD file will be generated, consist of the required information. Converting 2D to 3D made easy by drag and dropped the CAD file to Rhinoceros 3D software. An OBJ file as a simple data-format representing 3D geometry exported while Rhinoceros file format (.3DM) is useful for the geometry exchange. The OBJ file imported to Vuforia for mobile and tablet devices that enables the creation of 3D objects in real-time. The integration of ThingWorx and Vuforia along with Cloud and Big Data build a Digital Twin enabled UX for a vast number of individual wetlands.

This Digital Twin-enabled user interface (DT_i) is enabled by AR and IoT to envision individual local community members for taking an active part in maintaining wetlands. While wetlands have proven their advantages, it can be challenging to keep a high number of uniquely constructed wetlands. The nature of a wetland represents frequent changes due to climate, storm, flooding, and other natural consequences. Fig. 15 demonstrates a DT_i with significant value to individual community members by providing overlay live data for awareness, maintenance, education, and operations through visual access to the checkpoints in a wetland similar to collecting the available Pokémon species in a region where a game takes place. Besides, it can acquire instant feedback from customers and apply further backend processes.

This DTi was accomplished by obtaining GIS data from the Council's portal. Converting the 2D contours with 3D planar surfaces was the next step. Then the 3D model was developed in Rhinoceros 3D and imported directly in Vuforia, an augmented reality software development kit. The significant objects were segregated in separate layers, including the relevant infrastructure information, such as concrete pipes, pumps, valves, inlet, outlet, and concrete retaining wall. The water's top surface was given plugged in with the transparency, enabling maintenance engineers to understand the complex infrastructure, including underwater of each wetland.

The transparency feature in the DT_i allows users to change the water's opacity and visualize a real-time 3D model of a wetland. For example, real-time data representing the sediment level is collected by smart sensors and linked seamlessly to AR by using IoT, making an interchangeable 3D experience. DT_i beneficial for faster resolution, reduce maintenance time and cost, and even prediction regarding maintenance and operations. Besides, this DT_i allows every community member to report observations and issues by just clicking on the icon located on the bottom left side of the DT_i. This feature addresses the main business challenge, as everyone is one click away from providing valuable feedback to the Council. Therefore, DT enriches the user experience by providing instant 3D views along with overplayed real-time information and the option to share augmented multimedia feedback.

This DT_i solution is built based on the seamless integration of ThingWorx, an Industrial IoT and Vuforia, a Cloud-based AR software. Stakeholders can communicate with duty personnel to immediately identify issues, which can be valuable to the maintenance schedule of many unique wetlands in a wide area. Furthermore, each wetland has its

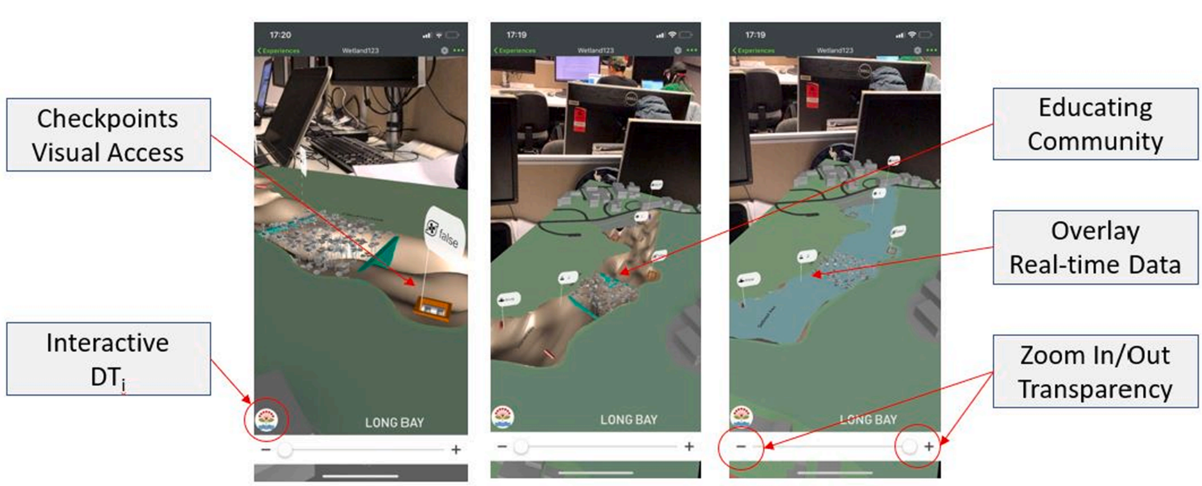

Fig. 15. A Digital Twin-enabled User Interface.

community feedback history that builds up a digital asset from the customer's perspective. This industry-led project was undertaken to address a significant environmental challenge through a Digital Twin enabled solution for a substantial number of unique constructed wetlands. Therefore, by mirroring the physical environment digitally, we can discover potential challenges, share resolutions between infrastructure in each wetland that too often is disconnected from each other to reduce uncertainty, offer better maintenance schedule, prioritization, prediction, and long-term strategic planning.

Fig. 16 illustrations how digital transformation empowers business by utilizing Industry 4.0 innovative technologies. Digital Twin provides valuable services, including a suitable user interface, instant information, and smarter maintenance for distinct infrastructure in constructed wetlands since the environment provide numerous ecological functions associated with people, plant and animal life. The AR-enabled UX provided by Vuforia View, an Android and iOS app to access and share AR experiences, that are rich with 3D content and IoT data on smart devices. Alternatively, the Digital Twin service allows the user to interact and move around the scene on a tablet or smartphone.

6.4. Insights and reflections

Getting the maximum value from the environment over time takes significant effort, including physical inspections, transportation to and from individual wetlands across the country, taking the sample to different laboratories, providing reports and consolidating in a timely matter, providing a user-friendly channel between users, engineers, contractors, and Auckland council and considering that each wetland should have its detailed maintenance plan to suit the particular catchment size, pollutant loads and inflows. In a traditional process, a full inspection of constructed wetlands should take place based on a fixed schedule after construction is completed, which is effective [59].

This study brought significant value to stakeholders, including the city council, third party community members, visitors, and engineering and utility vendors. This Digital Twin enabled system illustrates a digital transformation, which minimized physical inspections, reduces risk by real-time remote management, individualized service without extra cost, reduces wasted labour hours and asset downtime by connecting the live data to build information and knowledge for making fast and more accurate decisions for individual wetlands and as a whole.

The proposed DTaaS is different from several implemented Digital Twin systems in some respects. This case study differs from most industrial studies due to a significant number of unique and dynamic assets on a distributed scale. In contrast to earlier findings, however, no evidence of DTaaS was detected. However, there are similarities between this case study and observed Digital Twin case studies for using Industry 4.0 technologies, including IoT, XR, and Cloud. While most experiments tend to be more concerned with the technology, the proposed Digital Twin reference architecture model has a broad scope to include mass individualization.

The high number of widespread smart wetlands is heavily dependent on autonomy to make efficient and effective maintenance. DTaaS provides autonomy based on the proposed Digital Twin reference model by utilising Industry 4.0 technologies, including IoT, Cloud, Big Data, and XR. The real-time Digital Twin system brings advanced features to monitor, control, predict, and maintenance for the benefit and well-being of its people through IoT-enabled sensors and actuators through connectivity, data aggregation, and augmented user interface regardless of time and place.

Companies can predict outcomes more accurately, detect physical issues sooner, achieve precise feedback, offer instant alert, and build better products and services for most applications by using DTaaS. Business sectors can use Digital Twin to realize the full potential of these three 'P's' – Products, Processes, and Personalization. However, Michael and John [60] recognized three main obstacles that need to be addressed. "These obstacles are organizational siloing, knowledge of the physical world and the number of possible states that systems can take," To this end there is a trade-off between the business value and cost of creating Digital Twin. Consequently, the three 'I's' – Integration, Interval, and Intricacy should be considered before undertaking a Digital Twin.

- Integration level: How specific will the Digital Twin integration?
- Interval: How detail and accurate the Digital Twin should be?
- Intricacy: How much resource required for creating a Digital Twin?

Gartner expects half of all major industrial companies to be using digital Twin by 2021 and increasing their effectiveness by ten percent [61]. Industries often implement Digital Twin for aggregating real-time data from physical sensors to enable shorter design, speed up development, support change management, and optimize operations and performance. Digital Twin-enabled solutions have been developed to track dynamic state data, create a consistent improvement in efficiency, minimize failure rates, shorten development cycles, and open up new service-oriented business opportunities. The minimum viable Digital Twin is made possible by integrating IoT and AR for collecting real-time data and instant visualization.

Digital Twin tracks dynamic state information from each smart sensor and makes it available for monitoring, controlling, and prediction. Therefore, Digital Twin is often at the heart of the business transformation, which can influence performance. However, different understandings of Digital Twin can be observed in industrial practices. In this regard, Table 1. points to the leading companies utilizing Digital Twin to solve various business challenges. Surprisingly, Digital Twin for mass personalization has not been closely examined.

Cutting edge Industry 4.0 technologies have the potential to address complex problems. For instance, IoT brings significant advantages by collecting data from smart sensors, Big Data advance predictions, AR scale 3D experiences, and Cloud utilize an extensive amount of storage and process power. However, Industry 4.0 has not yet considered confronting mass individualization challenges once together. The proposed Digital Twin reference architecture suggests orchestrating these cutting-

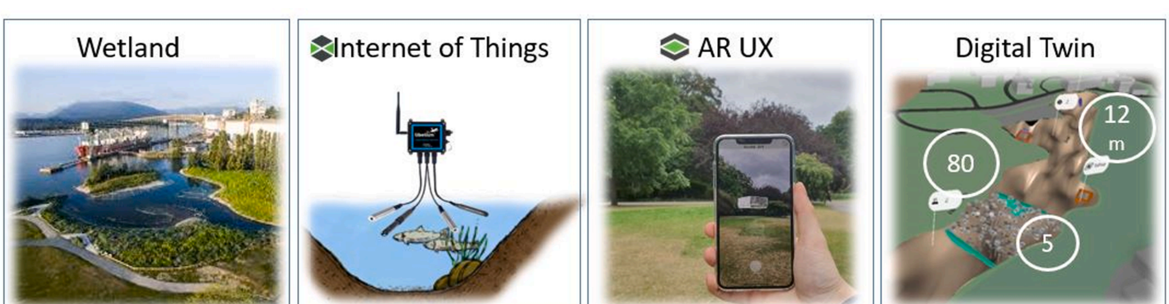

Fig. 16. Digital Transformation under Industry 4.0.

Table 1
Digital Twin observations limited in exclusive industries and applications.

Company	Main Digital Twin Value	Main Product/Service
Ansys	Simulation combined with analytics to make predictions.	Mechanical finite element analysis software.
Dassault Systemes	Design and simulation of a virtual factory.	Specializes in 3D design and product lifecycle management software.
Bosch	Manage inventory of Digital twins for IoT devices and analyze production processes.	Automotive parts, power tools, security systems, home appliances, engineering, electronics, Cloud, IoT
GE.	Performance improvement and forecasting.	Appliances, power, renewable energy, aviation and healthcare
IBM	Predict equipment failure; optimize maintenance schedules.	Cloud computing, AI, IoT, data analytics, Digital workplace.
Microsoft	Model the interactions between people, places, and devices.	Computer software, consumer electronics, personal computers.
PTC	Increase manufacturing flexibility & competitiveness.	Computer software and services include IoT and AR.
SIEMENS	Digital Twin for plan, design, and production systems.	Power generation, transmission, telecommunications, medical diagnosis, control systems.
TESLA	Synchronous data between every VIN* and the factory.	Clean energy and electric vehicle.

* Vehicle Identification Number

edge technologies for achieving a scalable solution aimed at distinctive [62] situations such as the maintenance schedule of constructed wetlands in a unique and dynamic environment.

7. Conclusion

The purpose of the current study was to get the best out of Digital Twin capabilities in response to the industrial transformation. The main goal was to determine a Digital Twin reference architecture model in Industry 4.0. The second goal was to introduce Digital Twin as a Service (DTaaS) on top of the proposed reference model. The third goal was to investigate the key Industry 4.0 technologies required for building Digital Twin. The results of this study state that Digital Twin enriches by utilizing Industry 4.0 technologies, including Cloud, IoT, and AR, to fuel the industrial transformation. This study set out to adopt RAMI, a well-recognized reference architecture model in Industry 4.0, and an Agile approach for different Digital Twin integration levels.

Digital twin solutions are made possible by digital modeling and digital thread as two key enabling capabilities. This study emphasized moving from on-premise modeling and simulation software to DTaaS, enabling enterprises to embed Digital Twin in their operations. In response, this study has examined the relationship across three axes in the proposed 3D layered model comprising the Digital Twin layers, Agile process, and Digital twin integration levels. This study also discussed the crucial Industry 4.0 technologies, which are thought to contribute to Digital Twin implementation. Besides, the authors coined "phyber," a blended concept due to the mutual influence of physical and cyberspace.

By integrating ThingWorx as an Industrial IoT platform and Vuforia as an AR software development kit, this R&D observed that Digital Twin is the most suitable technology to close the gap between the physical and digital worlds and made one of the first attempts to build Digital Twin toward mass individualization as the most challenging product and service development paradigm. Moreover, it is noteworthy through an empirical confirmation by an industry-led case study tackling a real-world challenge to maintain a significant number of constructed wetlands in a wide area with substantial value, including real-time monitoring, remote controlling, prioritizing, predicting, immediate alerting, and scheduling maintenance functionalities.

The research activities will stay active due to the expected value of Digital Twin integration with Blockchain and AI technologies. The former aims to meet a high level of transparency and data privacy and the latter aims to learn from experience and prediction without being explicitly program. The authors believe researches on Digital Twin agility and resilience are key attributes to continue operations safely, meet social distancing protocols, remote site visits, transparency in the supply chain, and increase automation, especially during global challenges such as unprecedented challenges with the COVID-19 outbreak. Therefore, further research is required while focusing on practical integration and interaction among the physical, digital, and cyber spaces.

Declaration of Competing Interest

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

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