Pervasive and Connected Digital Twins for Edge Computing Enabled Industrial Applications

Filippo Sanfilippo
Dept. of Engineering Sciences
University of Agder (UiA)
filippo.sanfilippo@uia.no

Even Falkenberg Langås
Tvillingfabrikken AS
even.langas@tvillingfabrikken.no

Halima Zahra Bukhari
Tvillingfabrikken AS
halima.bukhari@tvillingfabrikken.no

Stian Robstad
Tvillingfabrikken AS
stian.robstad@tvillingfabrikken.no

Abstract

A digital twin (DT) is a digital representation of a physical asset that serves as its counterpart — or twin. DTs differ from static, three-dimensional models in that they are continuously updated with data from numerous sources. In one continually changing world of pervasive computing, where computational and human intelligence are expanding everywhere, DTs can be regarded as the backbone for addressing the synergy of software, devices, movable objects, networks, and people. In this paper, we present a novel perspective for designing, prototyping and testing pervasive and connected DTs for edge computing enabled industrial applications. The provided paradigm allows for the creation of computational models for cloud computing as well as the transmission of data and computational intelligence through analytic platforms. A case study is presented to demonstrate the possibilities of the suggested framework. According to the outlined findings, the proposed architecture contributes to effective maintenance and management of infrastructures and facilities.

1. Introduction

The prosperity of nations is closely correlated to the status and development of the industrial infrastructure system. This is demonstrated through the dedicated target to “build resilient infrastructure, promote sustainable industrialisation and foster innovation” under the United Nation Sustainable Development Goal (UN-SDG) number 9, “Industry, innovation and infrastructure” [1]. The UN-SDG is explained as the worlds action plan adopted by all member states to achieve peace and prosperity for people and the planet. This might serve as an illustration of the urge for nations at all welfare levels to “Promote inclusive and sustainable industrialisation”, as it is worded in the UN-SDG target 9-2, and to “upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes”, as it is worded in the UN-SDG target 9-4. In this perspective, the adoption of digital twins (DTs) appears as a promising enabling technology. The origin of the DTs technique dates back to 2003 when Grieves proposed the concept for industrial product life-cycle management (PLM) [2]. Grieves characterised the DTs approach in terms of three different aspects: physical entity, virtual entity, and data connection. Because of its broad application possibilities, the notion drew a strong interest from academics and businesses right away, [3]. DTs have been effectively used for a variety of objectives in several application fields, including construction [4], aerospace engineering, robotics, smart manufacturing, renewable energy, and process industries [5, 6, 7]. As a result of its extensive use, the notion of the DTs has been interpreted in a variety of ways. A broadly accepted one was proposed by Glaessgen et al. in 2012 [8]. They defined the DTs as a multi-physics, multi-scale, probabilistic simulation of a complex product that employs the best available physical models, sensor updates, and other factors to mimic the life of its corresponding twin. A more actual interpretation

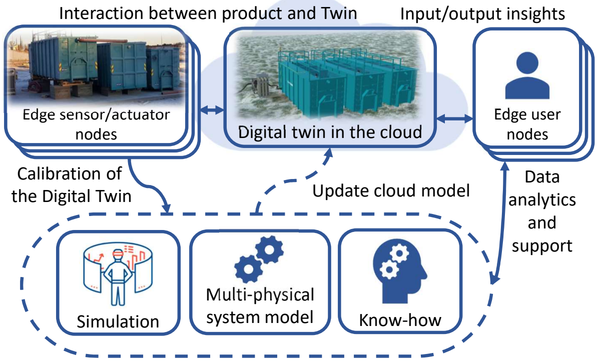

Figure 1. The adopted paradigm to building, prototyping, and testing pervasive and connected DTs for edge computing-enabled industrial applications.

defines the DTs as a digital representation of a physical item or assembly that uses integrated simulations and service data to store data from many sources throughout the product life-cycle [9]. This interpretation can be extended to encompass a synergy of software, devices, networks and people, which may unleash novel uses of DTs in factories of the future [10].

DTs can be viewed as the backbone for addressing the synergy of software, devices, movable items, networks, and people in one constantly changing environment of pervasive computing, where artificial intelligence (AI) and human intelligence are increasing everywhere. In this work, the concept of pervasiveness is borrowed from the healthcare field as a holistic vision of pervasive and connected assets, as defined by the so-called healthcare 4.0 [11]. This challenging pervasive DT evolution calls for new software architectures, network protocols and interoperable platforms, featuring levels of flexibility beyond the ones provided by the solutions available in the state of the art. Even though DTs have been successfully employed for a number of purposes in a range of application domains, the challenges of empowering edges of computer networks and adding computational intelligence to them have yet to be thoroughly considered. In this study, we adopt a new approach to building, prototyping, and testing pervasive and connected DTs for edge computing-enabled industrial applications, as shown in Fig. 1. The selected paradigm enables the development of cloud computing computational models as well as the transfer of data and computational intelligence via analytic platforms. To show the capabilities of the proposed framework, a case study is provided. In particular, a DT is designed for Slamrensing AS, a Norwegian company that provides cleaning solutions for entrepreneurs, process industry, mining, and energy processes. This is addressed through organising the paper as follows. A review of the related research work is given in Section 2. In Section 3, the proposed framework architecture is presented. The potential convergence of humans, “things” and AI in creating edge intelligence is also discussed. The considered case study is described in Section 4. In Section 5, simulation results are outlined. Finally, conclusions and future works are discussed in Section 6.

2. Digital Twin: an Industrial Perspective

In principle, DTs have surpassed the traditional notions of modelling & simulation in the following respects: a) DTs are characterised as high-fidelity prototypes of any given physical system/process, backed by continuous bidirectional data flow between physical and virtual entities. This continuous interaction enables DTs to emulate the functions and operations of their physical counterparts over their entire life cycle; b) the augmentation of information & communication technologies, namely the internet of things (IoT), big data science, and communication technologies (4G, 5G, and beyond networks) with virtual models account for yet another distinctive feature of DTs. These emerging fields are the key enablers in consistently replicating physical systems in real-time through their high-fidelity DTs.

The aforementioned technologies have led to the generation of massive volumes of data. Therefore, challenges related to the storage, processing, and subsequent analysis of big data can be handled through storage spaces and fast processing capabilities offered via cloud computing technologies [12]. While cloud computing technologies offer numerous benefits, they come with communication costs along with delays in process prognostics [13]. Contrary to cloud computing, edge computing is a bridge between the end user and the cloud facilities. Recently, the current trend is leaning more toward edge computing technologies to facilitate processing of important data/parameters in the vicinity of the processes. Technically, edge computing networks comprise computational hardware resources such as local servers running data compression techniques [13]. The analytical capabilities of edge computing are limited in comparison to cloud computing but nevertheless, edge computing offers optimisation of cloud computing resources [14]. Within edge networks, advanced statistical and machine learning (ML) algorithms [15] may be deployed to manipulate and extract useful information from a relatively smaller expanse of data generated through on-site interconnected field devices. This, in turn, may account for optimised process flows, timely insights, decision-making, and enhanced safety of the underlying physical processes without compromising on bandwidth limitation, latency, and data security. The complex processing tasks that are beyond the capability and the scope of edge computing are taken care of in the cloud infrastructure.

2.1. Practical Considerations in the Digital Twin Development

The development of a DT for any asset/process starts by replicating its physical characteristics through realistic 3D digital drawings and simulation. Advanced modelling techniques, specialised engineering software and simulation tools are used at this stage[16]. The choice of modelling and simulation tools that can best represent the desired properties and expected behaviour of the to-be-designed DT can be overwhelming at preliminary stage. This is due to lack of uniform understanding and consistent approaches across different disciplines for the intended DT representation [17].

The important aspect of DT development involves unobtrusive data connectivity between the twinning entities. The essential data acquired through physical sensors, cameras, laser scanners and IoT devices can be utilised for comprehensive representation and continual adaptation of the 3D digital models to their physical counterparts. Furthermore, data processing, data-driven simulations and analysis are carried out to optimally schedule plant operations, resources, predictions and maintenance activities. Thus, data-driven decision-making and prognostics significantly enhance the intelligence of underlying digital models and autonomy of plant operations.

The scope of DTs vary with the scale and requirements of the corresponding physical counterparts. For small and medium sized enterprises (SME), the right tools/expertise to successfully implement DTs are hard to come by. In such situations, the use of full stack service pool, outsourced to third party services is quite on the trend. By combining DTs and third party services, the significant value can be created from the underlying processes. These third party services can be scaled and may be used on demand while camouflaging the heterogeneity from various resources and vendors. The trending services in today's world of IoT account for computational resources, data storage & management, data transfer & communication, and, smart analytics, to name a few [6, 18].

In an industrial framework, a plausible approach may be to create libraries of virtual models for commonly encountered physical entities or manufacturing units. The encapsulation of virtual models in services can benefit the developers, the users, and the overall value chain of the DTs by reducing the lead time of DTs while rendering the reusability of services/libraries across heterogeneous platforms [19].

2.2. Digital Twin Applications

The requirements and the methodologies that need to be adopted for the deployment of DTs in different industries are subjective. Technically, the sludge treatment plants considered in the case study are related to the process industry, but their area of applications encompasses the construction industry.

The process industry is characterised by the facility running complex processes. The foremost barrier to the implementation of DTs in the process industry is to simulate the behaviour of the involved processes through dynamic simulations in real-time. So far, exact process models and their continuous updates are quite hard to come by, thereby accounting for the lack of practical implementations of DTs within the process industry [20]. A detailed overview of the existing trends, enablers, and barriers within the process industry is presented in [21]. However, from a process monitoring perspective, DTs combined with smart sensors and pervasive connectivity can serve to analyse critical process parameters, optimise operations, maximise profits, reduce costs and human-process interaction. A similar outlook has been adopted in this article.

Construction industry is another prospective domain where DTs can be deployed. Hitherto, the construction industry is perceived as the least digitalised of all the industries owing to the lack of innovation, lack of unified approaches and non-proprietary building information modelling (BIM) software [22]. BIM is essentially a digital representation of physical and functional characteristics of any construction facility. The case study proposes a different approach to DTs in the construction industry, where instead of making digital twins of constructions, the aim is to make DTs of the construction equipment, more specifically a sludge treatment plant. The designed DT enables workers at construction sites to carry out maintenance procedures more effectively with improved plant operations.

The recent advancements and ongoing research in DTs and other relevant fields will usher a new era of smart and innovative operations in nearly all industrial applications.

3. Proposed Architecture

This section describes the proposed architecture including hardware, software and communication protocols needed for a full pipeline system from raw sensor data to a structured and informative DT. The process starts with gathering data, which is then stored in the cloud. This information can be accessed/visualised in a DT, and potentially used for predictions in a decision support system (DSS).

Fig. 2 shows the proposed software architecture that could provide a platform capable of bringing the paradigm from Fig. 1 to life. It shows how plants, situated at different geographical locations, send data into an IoT backend system. The frontend DT then fetches the data from the IoT backend. The architecture also contains an authentication backend as well as another database (DB) for additional features such as

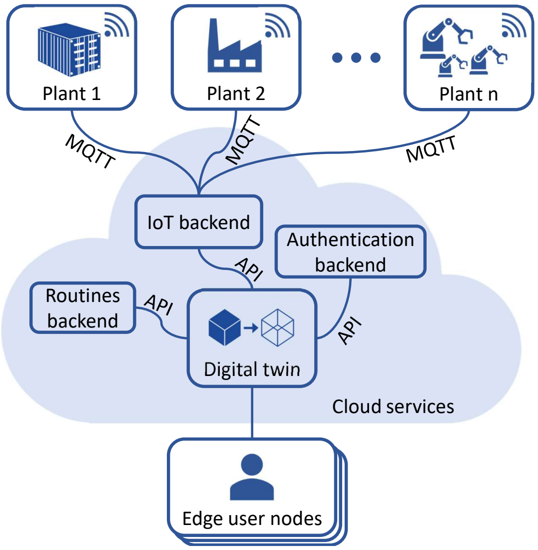

Figure 2. The proposed software architecture for edge computing-enabled industrial applications.

routines and routine logs. These are all hosted in cloud services. Even the DT can be hosted in the cloud, accessible on a website. To emphasise the flexibility of this framework, the diagram shows heterogeneous plants connected to the same IoT backend. Such a framework has provision for expansion, i.e., any plant or facility can be embedded into this cloud-based infrastructure, be it a production line, a robotic cell, a water treatment plant or farming equipment, to name a few.

Fig. 3 shows a sequence diagram for the proposed architecture. Note that the diagram is used hereafter to present blueprints (the real implementation of the system may differ). Fig. 3 explains the communication flow all the way, from the physical plants, up to the frontend DT. Step (1) in the figure is the IoT data transfer from the plants to the IoT backend, (cf. Section 3.2). This transmission happens with fixed time intervals and goes on for the lifetime of the data source. To access the data, an end-user starts with entering his/her user credentials in the frontend DT (2). Further on, the credentials are sent to the authentication backend through an application programming interfaces (API) (3), where it is verified (4) before an access token is returned to the frontend DT (5). The user roles are then queried (6), checked in the backend (7) and returned to the frontend DT (8). These roles can represent plants the end-user has access to. Therefore, they are displayed for the user in the frontend DT (9). Based on the roles displayed to the end-user, he/she may select to view a specific plant (10), causing the frontend DT to query data for that plant (11). It is returned from the IoT backend (12) before it is embedded in the DT (13) and displayed to the end-user (14). The user can read data, get alerts and interact with the 3D-model in the displayed DT. He/she can also update the routine log by giving inputs to a routine interface in the DT. These routines are stored in the cloud DB (15). At last, the end-user can log out (16-19), deactivating the access token from (5).

3.1. Gathering IoT Data for Edge Computing

Data is the backbone of every DT. Gathering data and publishing it to the cloud enables features like cloud computing, remote access, remote control and alert systems, to name a few. In addition, the crucial step of data gathering can also include real-time data processing.

Data gathering at the lowest level starts with sensors. For automation systems, these sensors are often connected to a programmable logic controller (PLC), where the sensor data can be used for the closed-loop control of systems. Advanced sensors support structuring of the data already before leaving the device, such as the Flow Thermal Meter for gases (FTMg) [23] from SICK, to name an example. This is typically done through a standard called Open Platforms Communications Unified Architecture (OPC UA). OPC UA is a cross-platform, open-source, IEC62541 standard for data exchange [24]. Structuring of data with this standard can provide the system with semantic interoperability as well as lay the foundation for a good data model whose benefits can be utilised all the way up to the frontend DT.

Today's industry comprises many offline PLCs working as a closed system. Industry 4.0 aims at expanding the scope of these closed offline systems by connecting them to the internet. A versatile solution that works in harsh environments without any Wi-Fi connection is to use state-of-the-art modems/IoT routers like the Ewon Flexy [25]. In addition to being able to receive data from PLCs or other hardware devices, this device provides the possibility for real-time data processing enabling another step of edge computing. It supports scripting in JAVA and BASIC giving developers huge possibilities for both data processing as well as publishing data to the cloud using industrial graded communication protocols like Hypertext Transfer Protocol (HTTP) based protocols like OPC UA or MTConnect as well as another protocol called Message Queuing Telemetry Transport (MQTT) [26]. For projects where more communication and edge computing options would be desired, a Raspberry Pi could be used together with

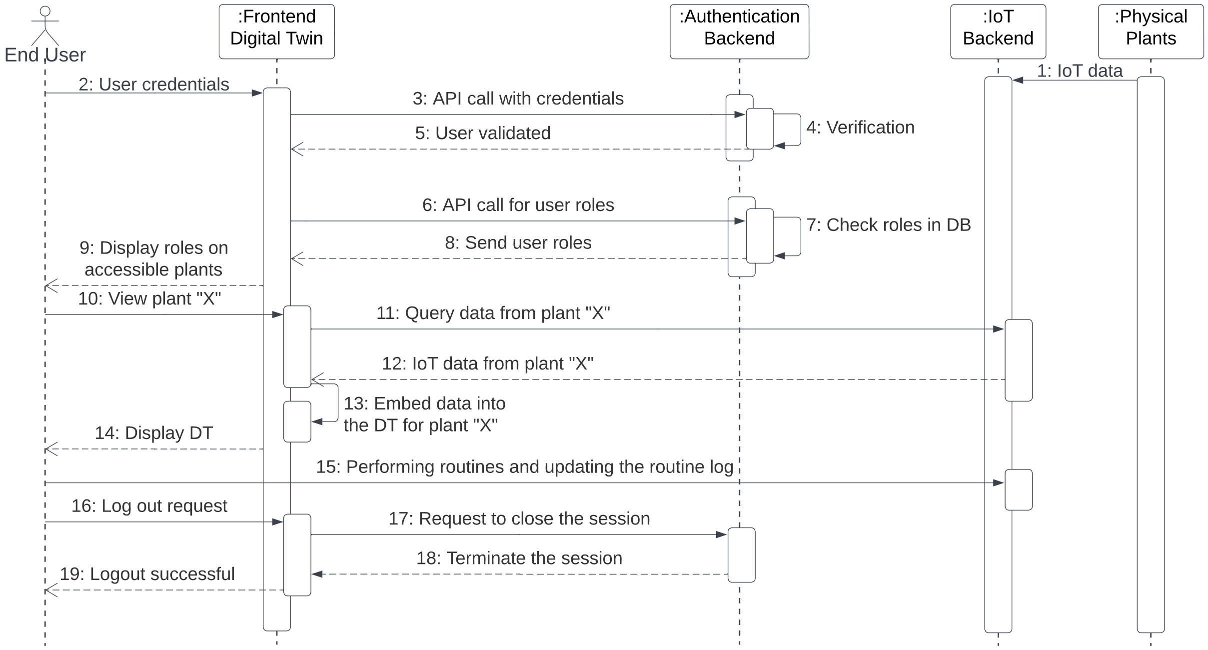

Figure 3. Sequence diagram for the proposed architecture.

a 4G modem. This would increase the complexity of the system with an extra hardware device, but it would enable a higher storage capacity, computing power and flexibility to the edge device. H. Huang et.al. proposed this in [26], though with a Wi-Fi connection instead of a modem, which would not be feasible in remote locations with no Wi-Fi. An Ewon Flexy modem was already connected to the relevant plant in the case study and was deemed adequate for the project.

3.2. Storing IoT Data for Cloud Computing

Either of the two protocols, viz., MQTT or HTTP may be used to populate a cloud DB from an IoT device. To choose between MQTT and HTTP, there are a few aspects that should be taken into consideration. An HTTP connection is only kept alive while sending the data. This enables for connections to multiple servers and can potentially handle large traffic. On the other hand, an MQTT connection can be upheld as long as the device is running, also allowing for a more complex connection with possibilities of using tokens, certification files and encryption, thereby enhancing the level of data security [27].

HTTP is normally used such that the IoT device is the HTTP server, while the cloud DB where data is stored acts as a client. The client queries data through GET requests. MQTT works in a different way. The IoT device is the MQTT client and can send data to the MQTT broker, or server at any times. This allows for highly customised data transmissions. For instance, the IoT device can send data only when certain values exceed a threshold. In addition, it can perform specific structuring and calculations on the device with complete control over what is being sent. This type of edge computing is highly relevant for the IoT domain, and it is the reason why MQTT generally is used on low bandwidth sites or for edge computing [27].

By utilising cloud services to host the MQTT broker, it can serve as a hub for an unlimited amount of IoT devices located at different geographical locations on different networks. Microsoft Azure has such a service out-of-the-box called the IoT Hub [28]. One of their competitors, i.e., Amazon Web Services (AWS), does not offer a similar service. Therefore AWS relies on third party software or some additional development project. Fortunately, a Norwegian based company called Dimension Four (D4) [29] provides such a crucial service for AWS.

Choosing a suitable DB for IoT is important to avoid performance issues when accumulating large amounts of data to enable efficient processing of big data. As stated in [30], NoSQL DBs is the preferred option for big data and IoT applications because of their efficiency and scalability.

3.3. Accessing IoT Data

When big data is stored in an efficient DB, it can be accessed into a frontend application, i.e., a DT. It is possible to get direct access to the DB remotely over the internet. This can be quite a simple approach, but on the other hand, it involves a big security risk with regards to a no-trust policy, which is becoming the standard within cyber security. By making use of APIs for data exchange over the internet, i.e., between the frontend application and the backend system, additional layers of security can be added including token based authentications, encryption, and scope-based user access/restriction. In addition, a good API can make it easier to query data as well as creating limitations to avoid overloading the backend system with large queries.

The two common types of APIs widely used in the above context are RESTful and GraphQL APIs [31]. One of the prime differences between the two APIs is that with the REST API, the client has to query the server several times to retrieve desired information from all the relevant data endpoints. This situation is analogous to inadequate data fetching against each query, thereby prompting the client to query again. On the contrary, against each endpoint, all the extra information is returned to the client, though unintended for the client. These two scenarios correspond to *under-fetching* and *over-fetching* of data, respectively. However, in GraphQL, the client has the flexibility to retrieve only the desired/specific information from the data endpoint with just a single query only. The query then returns the complete pertinent information in the form of a JSON string while saving the client from several queries or making multiple network calls back and forth between the DB and the client. Therefore, GraphQL APIs offer better efficiency as compared to RESTful APIs. Furthermore, the development with GraphQL at both client and server sides can be carried out in parallel, thereby speeding the development process significantly.

D4, the company providing the IoT backend for the case study of this article, offers a GraphQL API on top. To safeguard against querying massive datasets resulting in pummelling of service and data overloading, D4 has stipulated the maximum signals per query to 100 only. Furthermore, the feature to trace and invoice clients querying at huge expense has also been set up in place.

3.4. Visualising Data

DTs are emerging as a powerful way of visualising data for better understanding and decision making. Several different tools can be used to create DTs. Unity, V-Rep, RoboDK and Gazebo are just a few [32]. Gazebo and V-Rep are highly accurate and capable simulators, and RoboDK is exceptional for intuitive offline programming of robotic systems. However, these tools lack something important that Unity provides: customisability [32]. Firstly, Unity has various possibilities with regards to creating custom applications for different use cases. Creating comprehensive, informative, data-driven DT applications for end-users of different backgrounds require simple user interfaces (UI), tailor-made for the specific use case. This, together with advanced simulation capabilities, as well as integration with Robot Operating System (ROS) makes Unity a very suitable and flexible option for DT development [33].

The platform flexibility and level of customisability that Unity provides gives a potential for an efficient, intuitive interaction with the DT. Creating simple UIs, enables a convergence between humans and "things" in creating edge intelligence. The potential of using AI based data interpretation enhances the level of understanding even further providing end-users with cutting-edge technology at their fingertips without the need for deep technical understanding.

The end-users, be those highly-skilled engineers, construction site workers or non-technical managers, can use the DT as a DSS to stay well informed and make data-driven decisions. Further on, they can monitor the results of their decisions, and take actions based on that.

Unity provides cross-platform support with possibility to build apps for Android, iOS, Windows, Mac OS and Linux. It even has the possibility of making WebGL builds, enabling web browser based DTs that are not depending on any installations or specific operating systems and can be hosted in a cloud service. This cloud computing approach is great for meeting the specific needs of customers. Some might want to use a DT outside the office for in-field maintenance. In that case a phone app is the perfect tool. However, for management or real-time monitoring, a web browser based app might suit the need. It can be accessed at any time from any device giving the user a broad flexibility. A browser based app reduces the need for local computational power with the app placed in the cloud on a platform like Azure or AWS.

To present stakeholders with real-time data visualisation and analytics for a DSS, some of the commercially available software are: Power BI, Grafana, and Azure Time Series Insights (ATSI). All these softwares have support for querying data from the GraphQL API, which makes it viable for the case study. This implies that the same IoT backend may be used for both the DT and the dashboard without any change in the proposed architecture.

For rapidly expanding enterprises, the growth of data is in proportion to the expansion rate. This is analogous to the case study of this article, (cf. Section 4).

The primary goal is to prevent data blow up due to ever-increasing data volume. A scenario corresponding to poorly designed and computationally expensive flat data tables can be avoided by carefully modelling data tables in accordance with the enterprise preferences. Power BI is a powerful tool that offers efficient data modelling capabilities. By identifying relationships between different data entities within the data models, it is possible to avoid data redundancy, reduce data footprint, and improve the performance of data models. Due to advanced capabilities such as sifting through data, creation of customised tables, implementation of row level security, and ability to scale up seamlessly with the enterprise scale and size, Power BI has been chosen as a preferred tool for the creation of dashboards and periodic reports for the case study.

Displaying data for a long time period, say one year, requires a high bandwidth in order to fetch all the data for that period. One way of displaying data over longer time duration, while both lowering the bandwidth requirement as well as avoiding performance hiccups on low-performance devices, is to calculate some key performance indicators such as daily average or median, maximum and minimum values closer to the data source. It can be done in the IoT backend from Fig. 2.

3.5. Authentication and Data Security

To provide stakeholders with access to the enterprise web application, comprising mainly of the DT, the live data streaming, and custom smart visuals, an important consideration is to have a secure identity access management (IAM) solution in place. Any breach in customer data confidentiality or failure to comply with data protection legislation can backfire for both companies. Therefore, for keeping the user information safe from malicious cyber-attacks and safeguarding from the inadvertent dissemination of sensitive information to competitors or unintentional recipients, an off-the-shelf solution for IAM is outsourced to Auth0. Auth0 provides expert security services for authentication and authorisation that are fast to implement and easy to customise. With reference to this article's case study, an off-the-shelf solution from Auth0 sped up the production and deployment of the web application/portal with smart features like securing user information and access keys, assigning specific roles for users in different cadres, and hashing of passwords.

Outsourcing authentication procedures to domain experts can also help speed up production. Nowadays, different authentication companies, having expert knowledge and experience, provide commercial solutions relevant to authentication procedures and user DB management. Using a provider like Auth0 provides a dashboard to manage users and assign roles.

4. Case Study

The aim of this case study is to develop a DT for Slamrensing AS'[1] sludge treatment plants stationed at numerous civil engineering sites, e.g., mining works, drilling and energy well companies, tunnels, and stone processing industries, to mention a few. Primarily, the construction industry outsources sludge/water treatment solutions to the plants from Slamrensing.

The DT of Slamrensing's plants serves as a one-to-one visual interface for the operators on construction sites, thereby enabling them to understand core plant operations, view essential components/assets used in the treatment plants as well as enabling them to perform fault prognosis without needing Slamrensing's support personnel to travel to their far-flung construction sites. Furthermore, DTs provide intuitive interface for the operators to view troubleshooting guidelines and essential maintenance routines/procedures for different components, resulting in improved plant performance and reduced plant downtime. Wherein DTs, real-time access of Slamrensing's plants is provided for both Slamrensing AS' enterprise and clients to monitor the ongoing operations using live data visualisation and smart analytics with Power BI. Furthermore, the Norwegian government needs to be reported upon compliance with sludge cleansing regulations. Therefore, the generation of periodic reports, summarising the water quality parameters at every treatment plant, is provided through Power BI.

5. Simulations and Results

The proposed architecture is utilised to create a DT for the case study presented in Section 4. Firstly targeting operators, the DT application provides an intuitive UI for any user. Fig. 4, 5, 6, 7 and 8 shows some of the different tabs in the DT's UI. A video depicting the entire case study is available on-line at `https://youtu.be/ucsNbsLo6fM`.

Fig. 4 shows the default view of the DT, giving an overview of the entire plant. The "Assets" tab, (cf. Fig. 5), displays the main assets such as sensors, pumps and other equipment. Clicking on an asset provides the user with a detailed view of that specific asset including real-time data, a data plot with recent

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[1] The word "Slamrensing" translates to "sludge cleaning" in English.

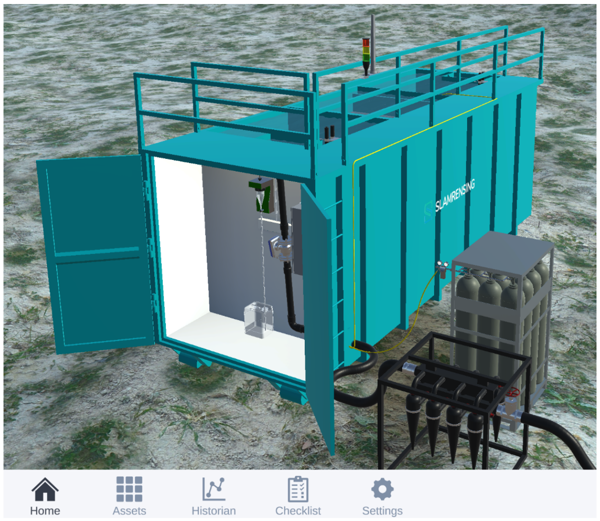
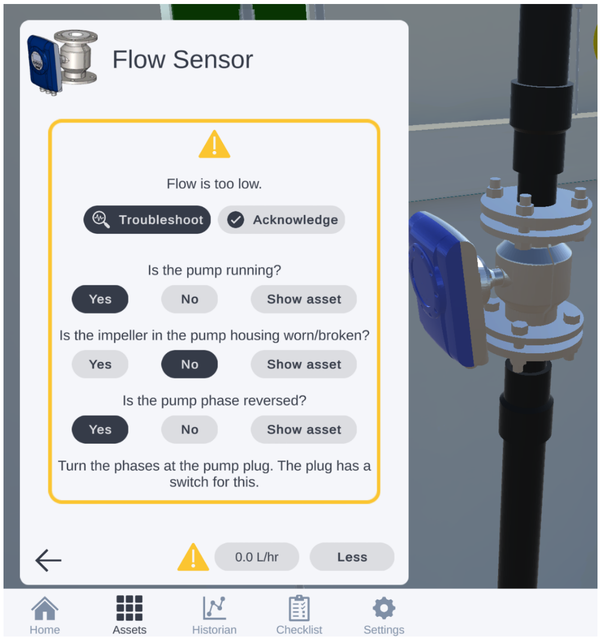


Figure 4. Default view of the twin.

Figure 5. List of assets containing sensors, pumps and other key components.


Flow Sensor

Flow is too low.

Is the pump running?
[✓ Yes] No Show asset

Is the impeller in the pump housing worn/broken?
Yes [✓ No] Show asset

Is the pump phase reversed?
[✓ Yes] No Show asset

Turn the phases at the pump plug. The plug has a switch for this.

0.0 L/hr

Figure 6. Troubleshooting guide for the flow sensor.

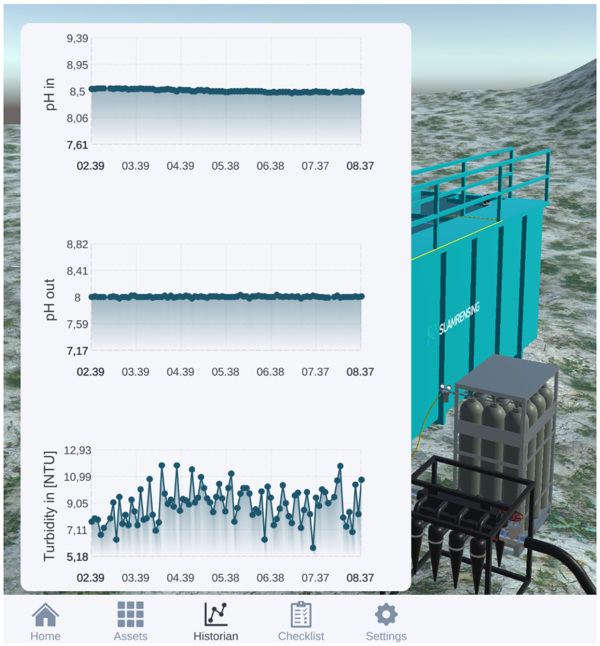
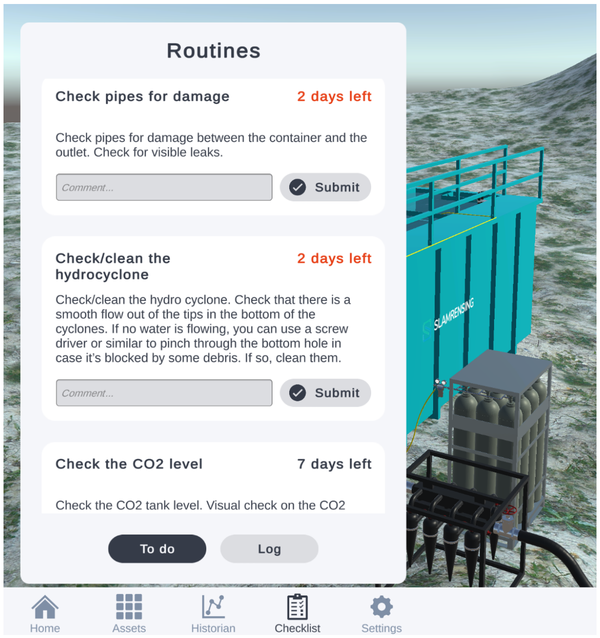


Figure 7. Historical data for the last hours.

data as well as a troubleshooting guide when an error or a warning occurs. The errors and warnings are based on variable threshold values, which are dependent on certain control parameters at the physical twin. Fig. 6 shows an example of a troubleshooting guide in the DT. Further on, it is possible to view a collection of recent data from all the sensors in the “Historian” tab, (cf. Fig. 7). A checklist with routines can be viewed in the “Checklist” tab, (cf. Fig. 8). This tab also contains a log of previously performed routines. The checklist is sorted based on the urgency, that is days left before expiry.

The charts, (cf. Fig. 7) display data over the last 6 hours. To keep the application fast and lightweight, the numbers of data points for each plot has been limited to 100. This enables the data view panes to be adjusted and viewed easily on any screen size or device type that the operators carry with them, ranging from old smartphones and tablets to laptops. E.g., to display data



Check pipes for damage — 2 days left

Check pipes for damage between the container and the outlet. Check for visible leaks.

Comment...

Check/clean the hydrocyclone — 2 days left

Check/clean the hydro cyclone. Check that there is a smooth flow out of the tips in the bottom of the cyclones. If no water is flowing, you can use a screw driver or similar to pinch through the bottom hole in case it's blocked by some debris. If so, clean them.

Comment...

Check the CO2 level — 7 days left

Check the CO2 tank level. Visual check on the CO2

Figure 8. Checklist sorted after expiry date.

for a year, the method proposed in Section 3.4 can be used. Instead of plotting all the data, only the average, minimum and maximum values would be plotted.

6. Conclusions and Future Works

A novel approach to developing, prototyping, and testing pervasive and interconnected digital twins (DTs) for edge computing-enabled industrial applications was presented in this study. The proposed paradigm allows for the creation of cloud computing computational models as well as data and computational intelligence transfer via analytic platforms. A case study was presented to demonstrate the possibilities of the proposed framework. Slamrensing AS, a Norwegian firm that provides cleaning solutions for entrepreneurs, process industries, mining, and energy operations, was designated as a DT. The suggested architecture, according to the findings, facilitates the proper maintenance and management of infrastructures and facilities. One of the main goals of this work is to boost global efforts to realise the wide range of application possibilities provided by DT and to give an up-to-date reference as a stepping-stone for future research and development in this domain. The main advantage of the proposed framework is that it is cross-platform, and it can even run on an internet browser. However, a drawback with running it in a browser is related to the complexity of the scene and the degree of fidelity, which could cause performance decays.

The Slamrensing enterprise can accrue enormous benefits with the ability to control programmable logic controllers (PLCs) or the connected human machine interfaces (HMIs) remotely via the DT. The PLCs at Slamrensing plants support secure virtual private network (VPN) connection over the Internet for remotely accessing, monitoring, controlling and programming operations on PLCs. The use of smart sensors, and modern industrial internet of things (IIoT) routers can go a long way in adding such capabilities within the DT. The proposed approach is somewhat analogous to what Kim et al. adopted in connecting a ROS-Gazebo system to control a PLC [34].

To further exploit the potential of DTs, virtual reality (VR) or augmented reality (AR) can be used, giving the end-user an even more comprehensive experience [35, 36]. AR could be used to overlay the DT data on top of its physical counterpart. The user would be able to perform maintenance with real-time data and informative descriptions supporting maintenance decisions during the actual labour. This also allows users with physical complications to maintain and watch over a project. It can also come in handy if the site or plant is on a remote destination where there could be multiple obstacles to get to the physical area. With all the capabilities DTs provide, the future works could go on for many pages, but the features mentioned above are considered the most relevant for the case study in this project.

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