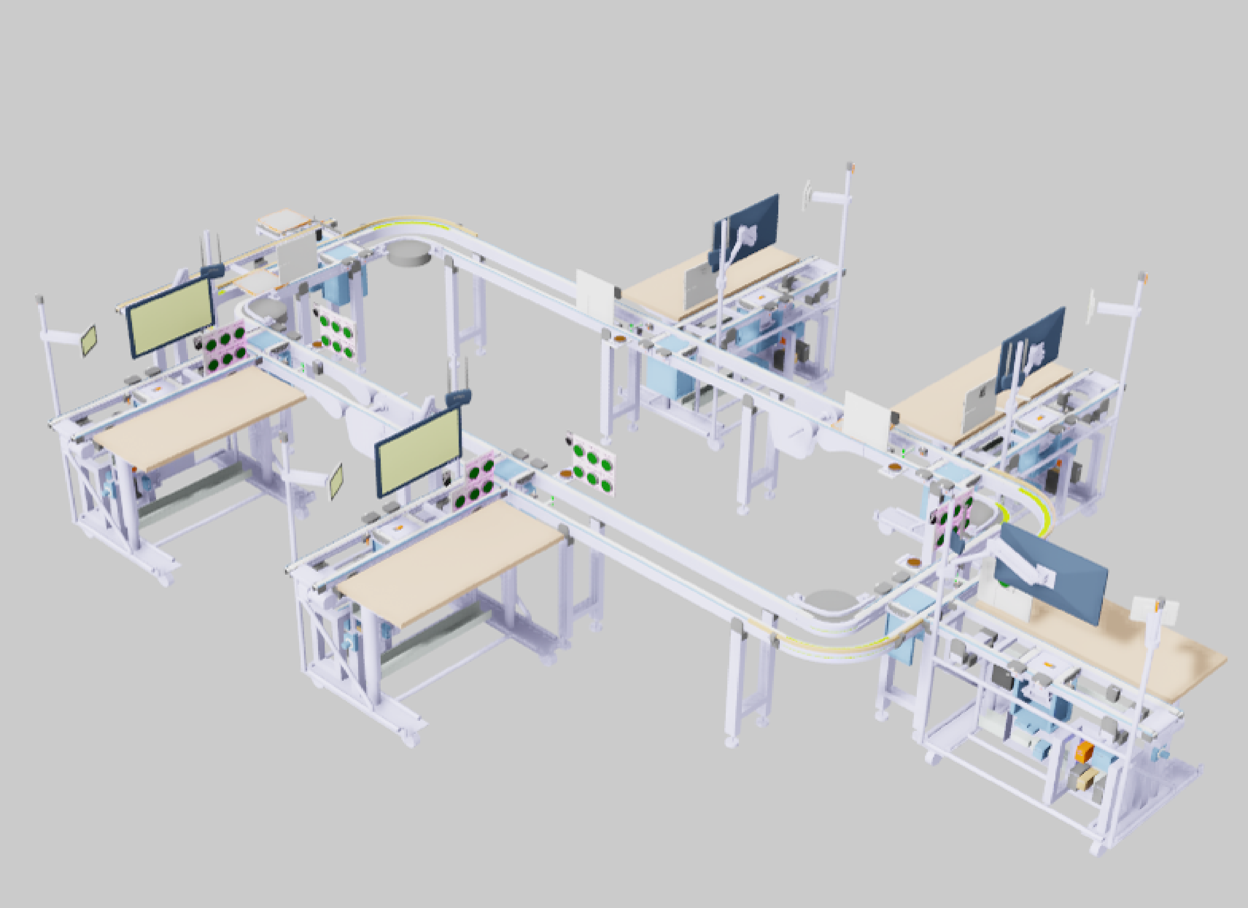

Dynamic Digital Twin Through VR

Enabled by Emulate3D

Master's thesis in Production Engineering

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Master's thesis 2024

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Abstract

As Industry 4.0 technology is still evolving, research and implementation gaps due to issues such as costs, security, and lack of domain expertise for enabling Digital Twins and supportive technology need to be bridged. This thesis proposes a practical framework for enabling the connection between an Internet of Things platform and Digital Twin-compliant software for constructing a Digital Twin based on the ISO23247 standard. The simulation software provides cognitive support for the user, immersing them in the Digital Twin through Virtual Reality. Connectivity with the Internet of Things platform facilitates real-time bi-directional communication, collaboration, monitoring, and assistance. An adopted research methodology with a foundation in empirical studies was used to support and validate the presented use case based on an assembly line for a lab-scale drone factory. The results showcase a Digital Twin with Virtual Reality functions of a real-world use case implemented based on ISO 23347, in addition to potential business values related to the benefits of Digital Twins enabled by virtual reality technology.

Keywords: Digital Twins, Virtual Reality, Internet of Things, ISO 23247, business values.

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Lejla Erdal & Ammar Gubartalla, Gothenburg, June 2024

Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

AMR	Autonomous Mobile Robot
AR	Augmented Reality
CAD	Computer-Aided Design
CNC	Computer Numerical Control
CPPS	Cyber Physical Production Systems
CPS	Cyber Physical Systems
DT	Digital Twin
FE	Functional Entity
ICT	Information and Communication Technologies
I/O	Input/Output
IoT	Internet of Things
ISO	International Standardisation Organisation
NPD	New Product Development
OME	Observable Manufacturing Elements
PLC	Programmable Logic Controller
RFID	Radio Frequency Identification
SII-lab	Stena Industry Innovation Laboratory
SME	Small and Medium-sized Enterprises
TTM	Time to Market
VR	Virtual Reality
XR	Extended Reality

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1

Introduction

This chapter introduces the master's thesis and illustrates the background of Digital Twins and the correlating research gap, giving a brief description of the stakeholders related to the development of the different constituents of digital twins, the problem statement with corresponding aim and research questions, together with the scope of the project.

1.1 Background

In recent years, the interest in Industry 4.0 technology within manufacturing systems has significantly increased. This is due to its capability to utilize big data in real time, facilitating communication and connectivity between digital and physical systems. This is imperative in today's rapidly changing markets, where increased resilience, responsiveness and adaptiveness are critical to a company's chance for success [1]. Technologies such as Digital Twins (DTs) are considered to be key enablers of Industry 4.0, as they play a vital role in transforming traditional industries by offering a real-time connected virtual representation of their real-world counterparts, enabling monitoring and remote control of manufacturing systems [7]. By incorporating Virtual Reality (VR), the user is immersed in the digital tool and can navigate and understand the environment, shifting the DT towards a more user-oriented perspective [8]. While DTs offer significant benefits in manufacturing systems and other industries, their value is not fully recognized in terms of reduced time to market, improved manufacturing equipment performance, and improved overall quality [6].

Studies have shown that there are still general concerns regarding the implementation of DT-related technology, such as Internet of Things (IoT) solutions. These concerns include challenges with platform connections and hardware, the scarcity of available domain expertise, obstacles in collecting and connecting data, costs, and security and trust issues between companies. However, even though DTs and their different applications have been explored and discussed in numerous research papers, practical implementation, especially using standardized frameworks, remains a significant challenge [9].

To address some of the implementation challenges, Rockwell Automation provides solutions for industrial automation and digital transformation, offering a wide range of automation solutions and services to various industries such as aerospace, automotive, food and many others. Rockwell's Emulate3D will be the primary software for constructing and building the digital copy. It allows users to create virtual representations of the physical systems, enabling them to design, test, analyze and optimize various manufacturing processes [10]. Using VR technology enhances competitiveness in a market with evolving technologies and increasing demand for sustainable production, where companies are heavily investing in these technologies [11]. By incorporating VR, the user is immersed in the digital tool and can navigate and understand the environment, shifting the DT towards a more user-oriented perspective [8]. Furthermore, the technology provides the opportunity to transport plant personnel to a virtual world where they can train on systems without consequences, predict future performance, and simulate line changes [12]. The software integrates with VR technology such as the HTC Vive headset with controllers, to provide realistic simulation, as well as synchronizing with IoT platforms such as Thingworx (PTC, Boston, USA) which will provide real-time connectivity.

To facilitate the usage of the DT software and the IoT solution, the lab-scale drone factory at the SII Lab will serve as a testbed to demonstrate the creation of a digital twin through VR. The Stena Industry Innovation Laboratory (SII-Lab) is a research facility affiliated with Chalmers University of Technology, Gothenburg, Lindholman, providing opportunities for the Swedish industry to test the digitalized production of the future. The facility is dedicated to studying, analyzing, and evaluating various technologies, including robots, artificial intelligence, digital twins, and advanced computer networks [13].

1.2 Research Gap

Recent research has consisted mainly of general frameworks for DT applications ([14];[15]) and there is, therefore, a lack of case or domain-specific studies, as well as insufficient research regarding evaluation- or metric-based implementation of DTs [9]. In support of standardisation in terms of DT application, ISO 23247 Digital Twin Framework for Manufacturing has been developed, which regards overview and general principles, reference architecture, digital representation, and information exchange [14]. The provided framework will aid in the construction of a real-time connected DT, with the provided reference architecture and integration methodology.

Aside from the research gap, there also exists an implementation gap, as the associated technology such as big data, machine learning and IoT is still evolving. For instance, the collected data is often in different formats, unstructured, or in some cases not collected. Regarding machine learning algorithms, the lack of sufficient data also affects the outcome, together with the lack of data scientists with the proper domain knowledge. For IoT solutions, the sensors, connectivity platforms and hardware are still under development which restricts DT implementation [9]. The lack of domain expertise that can interpret the data that is utilised for building the digital twin, as well as the results produced from it, is especially noticed in small and medium-sized enterprises (SMEs), in the combination of motivating the costs for implementing DTs [14]. Another issue is rooted in security, as the data needs to be handled properly, and in addition, companies in collaboration struggle with trust issues towards each other [9]. As for DTs integrated with VR, the conventional methods of showcasing the benefits of digital twins are often limited as they lack the necessary tools to emulate and demonstrate complex details in a visually appealing and user-friendly manner compared to VR [16].

1.3 Problem Statement

Although there are successful implementations of DT in both research academia and industry, a fundamental challenge lies in establishing connectivity between the virtual and physical systems. In this context, connectivity refers to the communication protocol enabling synchronous interaction between a virtual model and its physical counterpart. The objective is to facilitate real-time control and movements of physical entities while ensuring that the digital twin accurately replicates these actions [17]. The problem is to address how this data connection operates between the virtual model constructed by Emulate3D and the lab-scale drone factory ensuring a connection capable of bidirectional data transfer. Furthermore, the thesis will also showcase the benefits of DTs within a VR environment with the help of a use case linked to the business values of DTs.

1.3.1 Aim

The first aim of this thesis project is to apply a framework and establish real-time connectivity between the DT and the physical system, enabling the creation of a DT. The focus is to achieve synchronization between the virtual model and the real system allowing the digital twin to mirror the physical system in real-time. The second aim is to showcase the benefits of DTs enabled by VR, providing real-time interoperability and connectivity. Emulate3D will be used to build a digital copy of the lab-scale drone factory at the SII lab at Chalmers University Lindholmen, whereas Thingworx will serve as the IoT platform for this integration. The expected outcome is a methodology for constructing the real-time connectivity for a VR dynamic DT, together with a case study demonstrating the business values linked to the benefits of a DT enabled by VR.

1.3.2 Research Questions

This thesis posits that practical implementations of the DT concept using standardized frameworks can support scalable value creation, and the synchronization strategy is one of the main elements of DT implementation. The synchronization strategy regards an IoT platform, responsible for the simulation model's and real system's real-time connectivity. Besides establishing connectivity between the IoT platform and the DT software, the thesis aims to describe the potential business values linked to the benefits of implementing VR technology within the DT concept, which will lead to the following research questions (RQ):

- **RQ1:** *How to use DT standards to support the integration of simulation software and an IoT platform establishing a real-time connectivity?*
- **RQ2:** *What are the potential business values related to the benefits of DT enabled by VR?*

To answer these questions, the main objectives are to propose a practical example of the real-time connectivity implementation supported by the ISO 23247 framework. This example should be considered as an instance of DT implementation, not a recommendation or a standard itself. The other main objective is to present the benefits of DTs enabled through VR by linking them to business values. In order to achieve these two objectives, the thesis will follow these specific objectives:

1. Develop an integrated DT reference architecture applying the ISO 23247 standard framework.
2. Development of VR integrated Simulation Model to represent a Lab Scale Real System.
3. Propose an architecture to establish connectivity between a simulation model and its real system.
4. Demonstrate the real-time connectivity of DTs through a proof-of-concept use case.
5. Showcase potential business values of DT technology enabled by VR linked to the benefits.

1.4 Scope

The time frame for this project is scheduled to run through a duration of 20 weeks with a start in late January and a finish in June 2024. To ensure that the project is finished in time, CAD files will be provided for the VR software, and the base for the virtual factory will be built beforehand.

The project is limited to only utilizing DTs through VR technology. This means that no other types of DTs will be incorporated to evaluate and understand the data gathered from the DT, where the focus will be on the capabilities offered by VR technology. Detailed technical aspects of the proposed framework are outside of the scope of the project as well, it will serve as an empirical study based on the facilities provided by the SII-lab for similar use cases. To serve as a theoretical base for the project, literature studies will be conducted throughout the entire process, to ensure validity and to provide a link to the empirical studies with connections to research.

Moreover, only Emulate3D DT software and Thingworx's IoT platform will be implemented and evaluated. The case study will regard the lab-scale drone factory, while conclusions will regard further possible applications with the hopes of bridging the implementation gap for relevant industries. The application domain will however only regard manufacturing processes.

2

Theoretical Background

This chapter presents the theoretical background related to the thesis. A literature review was conducted on several interconnected topics that form the foundation of this project, supplemented by information gathered from software web pages. The topics include the shift from Industry 4.0 to 5.0, DTs and their functions, encompassing benefits and various perspectives on implementation; the maturity index for DTs; VR and simulation, covering relevant terms and applications; IoT systems, including their components and configurations; the three pillars of sustainability; and the business value of DTs. This literature review will facilitate the connection of theory to practice, enabling the verification and validation of the use cases through methods rooted in research.

2.1 Digitalization

Digitalization is herein defined as: ”The use of digital technologies to change a business model and provide new revenue and value-producing opportunities; it is the process of moving to a digital business” [18]. IoT platforms are key enablers in transforming and developing digital production and smart factories, as these platforms make it possible to connect the entire manufacturing process. The concept of digitization involves utilizing information technologies to facilitate the integration of emerging technologies, such as IoT and related services and tools, into various processes. This integration aims to optimize the manufacturing industry, resulting in more efficient and flexible production systems [19].

2.1.1 Industrial Revolutions and Industry 4.0

The fourth industrial revolution also known as (Industrie 4.0 in German) originally came from a project in high-tech strategy in Germany in 2011. It advanced the concept of Cyber-Physical Systems (CPS) into Cyber-Physical Production Systems (CPPS) [2]. It emerges following definitions of the first three industrial revolutions, where all four revolutions can be seen in Figure 2.1.

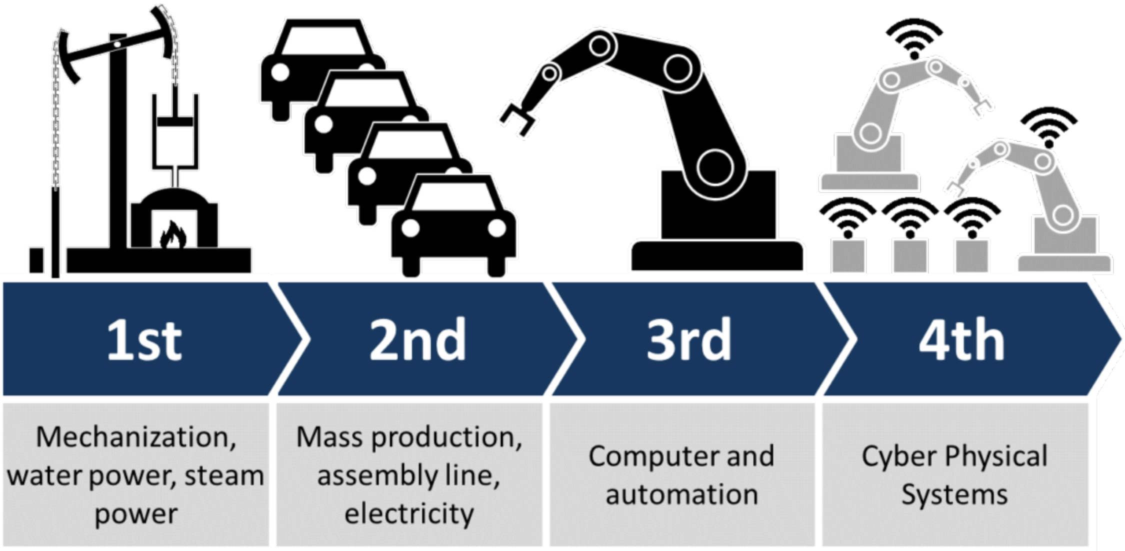


Figure 2.1: The four industrial revolutions.

The First Industrial Revolution marked the transition from manual production to machines using steam power. The Second Industrial Revolution introduced mass production techniques, including moving assembly lines, which significantly increased productivity and economic growth. The Third Industrial Revolution witnessed the advancement of information and communication technologies (ICT), such as the adoption of computer numerical control (CNC) and industrial robots, facilitating automated production processes [20]. Internationally, several countries have introduced similar initiatives, for instance, Produktion 2030 (Sweden), Industria 4.0 (Italy) and Industrial Internet Consortium (USA). In summary, Industry 4.0, initially perceived as mainly technology-driven, now has some considerations from societal needs, such as sustainability and human-centricity are visible [2].

2.1.2 Maturity Index for Digital Twins

As more companies strive for industry 4.0 potential, they struggle with the transformation due to various factors affecting the organization such as company objectives, the level of focus on the technology or issues with scaling up the implementation. Industry 4.0 maturity index helps companies to determine which stage they are currently at in their transformation into agile companies. It assesses them from a technological, organisational and cultural perspective, focusing on the business processes of manufacturing companies. As seen in Figure 2.2, the maturity index comprises six developmental stages, each building upon the previous one. Each stage describes the capabilities required to attain it and the resulting benefits and added value to a company. the first two stages however are not within industry 4.0, yet rather than focusing on establishing a foundation for industry 4.0 adoption [1].

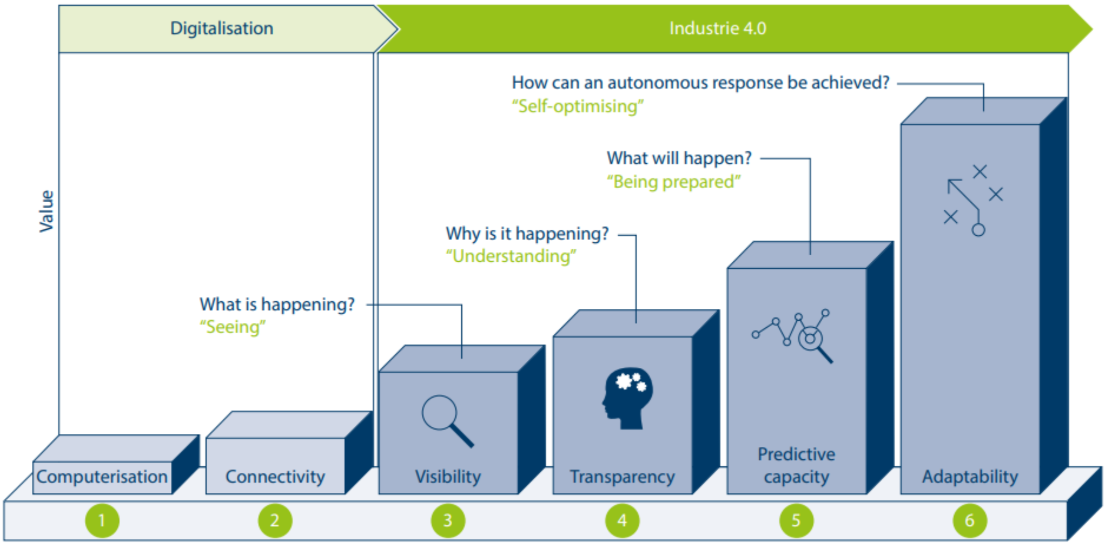


Figure 2.2: Maturity index for manufacturing companies [1].

2.1.3 Shifting Towards Industry 5.0

While Industry 4.0 has been driven by remarkable technological advancements, there are some considerations regarding sustainability, social needs, and human-centric concerns that need to be addressed [2]. To tackle these challenges, the shift towards Industry 5.0 began in 2017, and academic efforts continuously pushed for the introduction of the Fifth Industrial Revolution. In 2021, the European Commission officially called for the Fifth Industrial Revolution, titled "Industry 5.0: Towards a Sustainable, Human-centric, and Resilient European Industry" [3]. The adopted Figure 2.3 illustrates the three interconnected core values: human-centric, sustainability and resilience. In summary, Industry 4.0 is technology-driven, while Industry 5.0 is value-driven, and the former needs the latter for the sustainability aspects, while the latter depends on the former for the technological advancements and solutions [2].

Figure 2.3: Core Values of Industry 5.0, adopted by [2]. [3]

The concept of Industry 5.0 aims to achieve societal goals beyond merely creating jobs and economic growth. It emphasizes industry and production within the boundaries of our planet while prioritizing the well-being of workers at the centre of manufacturing processes [3]. To integrate social and environmental pillars into technological innovation, the focus must shift from individual technologies to a systemic approach. As technology continues to develop, it fundamentally changes how value is created, shared, and distributed. In this sense, these advancements align with the values society prioritizes in the future. These shifts prompt the industry to reconsider its place and responsibilities within society [21].

2.2 Digital Twins - Description, Perspectives, and Potential Benefits

The concept of a DTs [22] serves as a dynamic mapping between physical objects and simulation models, converging physical and cyber layers of a system. This solution facilitates interconnection, interaction, control, and management on the shop-floor level, supporting the advancement of smart manufacturing practices [23]. One straightforward benefit of DT is assessing systemic issues in complex systems, which often emerge due to human interactions during operations [24]. Furthermore, DT implementations effectively enable data-driven and smart manufacturing, setting the foundation for the other Industry 4.0 technologies [25].

Figure 2.4 illustrates the three main components of DTs consisting of the DT, the physical system and the IoT platform. The IoT platform collects real-time data from the physical system via sensors and actuators. It manages and stores the data, and then updates the DT in real-time. The DT processes the data, producing value and insights, which can be used to manage the physical system in return [26].

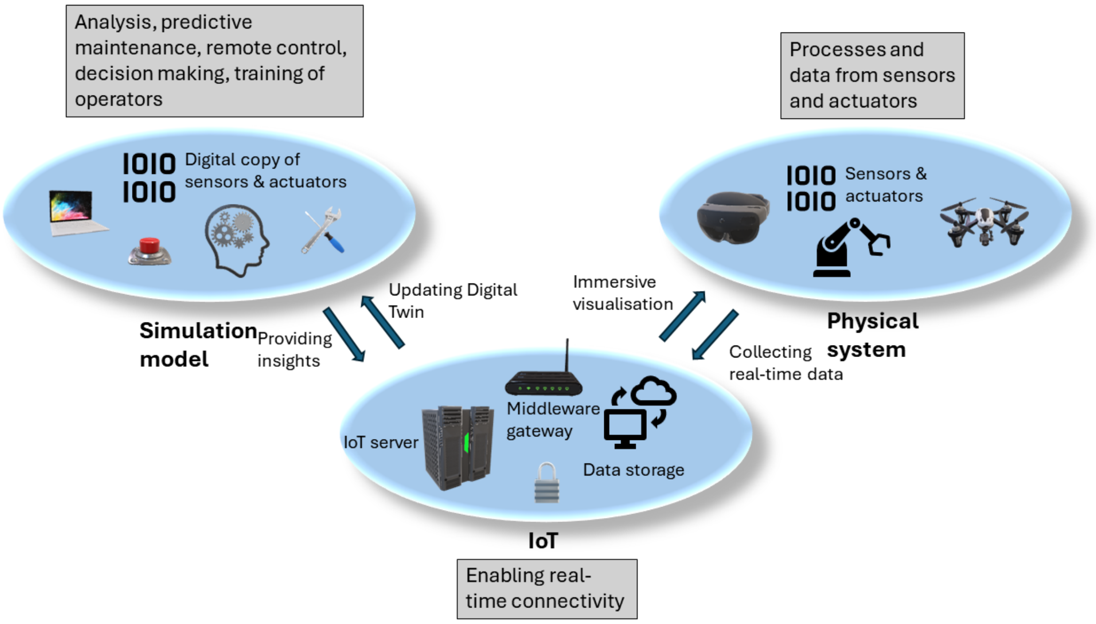


Figure 2.4: Visual representation of digital twin processes and components.

The literature on DT presents work focusing on different perspectives of its implementations, from the catalogue of system architecture patterns in DT design [27], to the detailing of scope and structural design requirements for DTs [28]. The need led to the development of the ISO 23247 standard for DTs, which addresses the interdisciplinary challenges of DT development providing a framework for manufacturing DT implementations [29]. The ISO 23247 framework was also illustrated through manufacturing cases, discussing the diversity of tools and integration needs for DT [30].

A broad study on DT applications in the manufacturing field highlights their use in process monitoring, life prediction, and asset management that demonstrate significant operational efficiencies [31]. Other practical cases of the ISO 23247 implementations are given in this section, where the framework has been applied to model DTs for flexible manufacturing cells, emphasizing key features and product lifecycle integration [32].

The main functions of DTs are supporting decision-making, enhancing visibility, optimizing operations, and increasing resilience to disruptions [33]. Credibility challenges in manufacturing DTs lead to the need to emphasize the importance of verification, validation, and continuously maintaining credibility to ensure trust and reliability [34]. The benefits of integrating immersive VR with DTs, such as improved visualization and interaction, can be achieved while addressing challenges such as complex VR design, better hardware controls, and communication strategies [35]. These insights show the DTs' transformative potential across various sectors, addressing challenges such as in unifying communication interfaces and lacking efficient modelling frameworks [36].

2.2.1 Business Values of Digital Twins

Depending on a DT's purpose and the level of sophistication needed for deployment, [26] propose two different models for selecting appropriate technological capabilities, called need pull and technology push. Need pull is applied when management strives for a specific value or advantage for deploying a DT and is inherited from the improvement of work. The value evaluation regards what has been improved and its perceived value, where the terminated value needs to be measurable, quantified and directly affected by the provided technology. For the value to be transferred, the organisation's transformation is required as well, such as different workflows, data management and methods for materials and equipment deliveries. Technology push is related to a company's inspiration of deploying a DT without a necessary use case, where the driver is connected to data and models together with performance. The technological evaluation regards the available data, algorithms, models, software and programming abilities within the company. As for the evaluation of performance, characteristics such as minimal time for performing tasks, accuracy and the minimal requirement of human effort are preferred.

For a successful implementation, a balance is needed between the available technological capabilities, and the potential value a DT can offer a company, and it can therefore vary between cases. An appropriate level needs to be selected in terms of the complexity of the DT, and the value needs to be translated into a business model for the top management to adopt. However, trade-offs can occur if the targets are conflicted, and companies can struggle with misinterpretation of value and performance measures, in addition to setting up ambiguous targets that do not support the deployment of a DT [26]. Aside from strategic performance and marketing dynamics being the focus of a DT, it can improve other metrics within manufacturing such as key performance and efficiency [6]. Tangible metrics such as those listed in Table 4.2 can further motivate manufacturing companies to implement DTs, as especially Small to Medium-sized Enterprises (SMEs) experience difficulties regarding efficient, effective and correct implementation [37].

Table 2.1: Business value categories for DTs and their potential, adapted from Deloitte Insights report [6].

Category	**Potential**
Quality	• Improve overall quality • Early prediction and detection of quality trend defects • Control quality escapes and ability to determine when quality issue starts
Warranty cost and services	• Understand current configuration of equipment in the field for efficient service • Proactive and more accurate determination of warranty and claims issues for reduction of overall warranty cost and improvement of customer experiences
Operations costs	• Improvement of product design and engineering change execution • Improvement of performance of manufacturing equipment • Reduction of operations and process variability
Record retention and serialization	• Creation of digital record of serialized parts and raw materials for recall and warranty claims management
New product introduction cost and lead time	• Reduction of time to market for new products • Reduction of overall costs for new product • Improved recognition of long-lead-time components and impact on supply chain
Revenue growth opportunities	• Identification of products ready for upgrade in the field • Improvement of efficiency and cost for servitization

2.3 Virtual Reality and Simulation

Simulation and VR are key technologies revolutionizing various industries, particularly for manufacturing optimization. Simulation involves creating a digital representation of a system or process to analyze its behaviour or performance. It is instrumental in optimizing production systems, as it allows for scenario testing and decision-making based on predicted outcomes [38]. VR, on the other hand, refers to an interactive computer-generated experience that simulates environments or situations, often using immersive technologies. In a literature review [39], with a focus on the convergence of these concepts, it was noted that integrating VR technology into DT applications can enhance visualization, interaction, and user experience. In manufacturing optimization, VR can be used for real-time visualization of production processes, enabling better decision-making. VR tools like HTC VIVE or Oculus Rift described in the use case [40], can facilitate real-time optimization by streaming high-resolution graphical representations of simulation models. Additionally, this integration allows users to navigate a digital environment using these wearable devices, accurately replicating the characteristics of the real-world counterpart at all times [41].

Moreover, manufacturing companies can shorten their time-to-market (TTM) in new product development (NPD) processes by incorporating VR [42]. Research and applications involving VR have grown steadily across various sectors, including the automotive and heavy machinery industries, largely due to the potential benefits it offers [43], [44]. Although the value of VR and DTs is significantly established in theory, their widespread adoption is hindered. VR technology is highly complex, often requiring high skills that many companies, particularly SMEs, do not possess internally. Furthermore, using 3D modelling software or CAD tools can be extremely time-consuming and challenging, and these factors can collectively deter companies from adopting this technology [41].

2.4 IoT - Architecture Description

An IoT system enables connectivity between the physical system and the simulation model with the help of connected devices such as sensors and actuators. The collected data is stored and used by applications for different purposes such as predictive maintenance, analysis, monitoring, control and optimization [45]. A company can also choose between proprietary IoT solutions with built-in functionalities, or create their own by using free open-source solutions [4].

The architecture used for describing the different components is based on the IoT reference architecture proposed by [4]. As seen in Figure 2.5, it comprises sensors, actuators, the IoT platform, a communications network, an IoT gateway, applications, security, and management. The sensors capture information supplied to the user, such as a sensor that detects the arrival of a pallet. This information controls the system by using the actuators, which convert the command to a physical action based on a request from the IoT platform, such as a mechanical stopper that blocks the pallet from moving past a specific point unless a request is made. Among integrating and managing devices such as sensors and actuators, IoT platforms also enable user interaction, management of systems, data and security, data storage and analytics, as well as allowing the usage of applications, which utilize the input and output from devices to perform tasks and services. One or more middleware components called IoT Gateways ensure that the IoT platform can communicate with devices via common communication networks, data formats and data layer protocols. As for data layer protocols, which are required to exchange data between IoT platforms and devices, a common model is the client-server model. A client device can then directly send data to a server, which in turn performs the request by providing a function or a service to the client. Security is handled with encrypting combined with monitoring keys and certificates, whereas management regards tasks such as system performance and configuration, networks, fault management, and service updates.

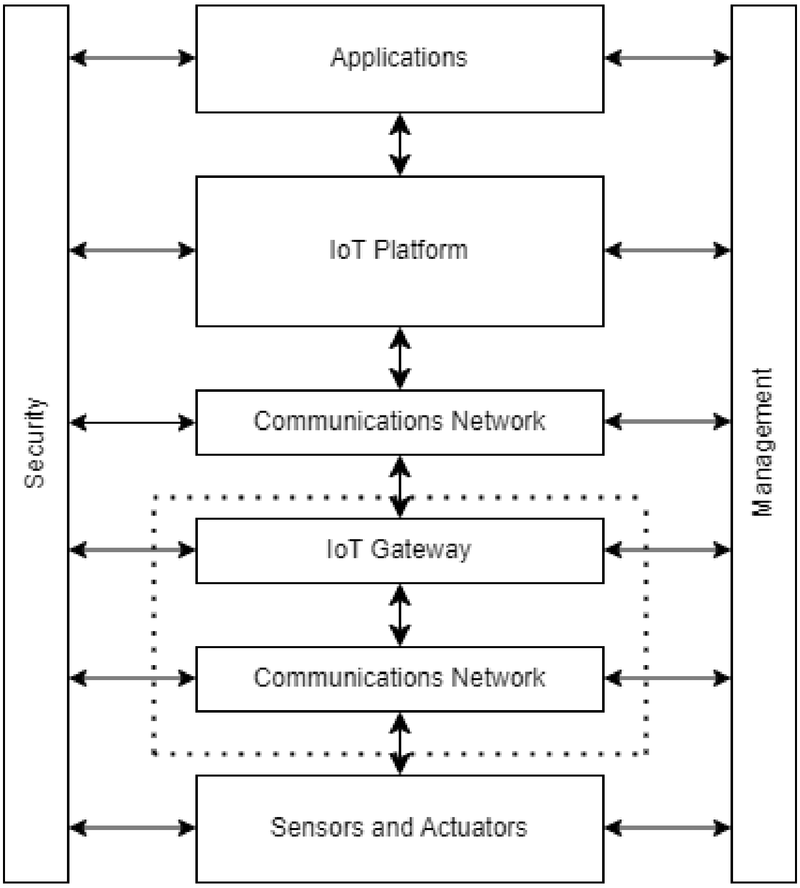


Figure 2.5: Adopted IoT architecture by [4]

3

Methods for Research and Implementation

The project aims to realize real-time connectivity between the simulation software and the physical production system, with VR as a human-centric approach for better interaction, accessibility and cognitive ergonomics. This integration allows designing, testing, analyzing, and optimizing manufacturing processes in a virtual environment. Traditional methods of demonstrating the benefits of DTs often fall short as they lack the tools necessary to emulate and present complex details in a visually engaging and user-friendly manner. Moreover, a significant challenge within DT frameworks is establishing effective connectivity between virtual models and physical systems. This connectivity involves setting up communication protocols that enable synchronous interactions between a simulation model and its physical counterpart, providing a necessity for the proposition of a framework for VR-based DTs based on industrial standards. The following sections will introduce the research methodology, literature review, description of the lab-scale drone factory, ISO 23247 reference architecture, VR integrated simulation solution, and the construction of IoT architecture. All of the technological solutions are proposed in consultation with industry experts.

3.1 Research Methodology

This section presents the methodology and the work procedure used in the thesis. The research methodology for this project will be based on the adopted research methodology by [27], together with the empirical study methodology by [46] to suit the proposed use case and the theoretical structure of the project. The resulting methodology can be seen in Figure 3.1.

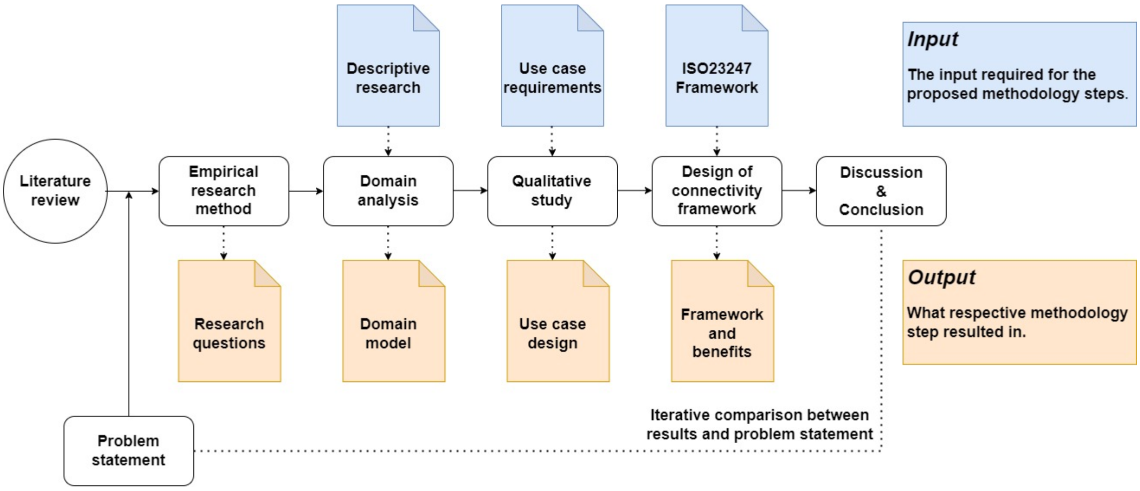


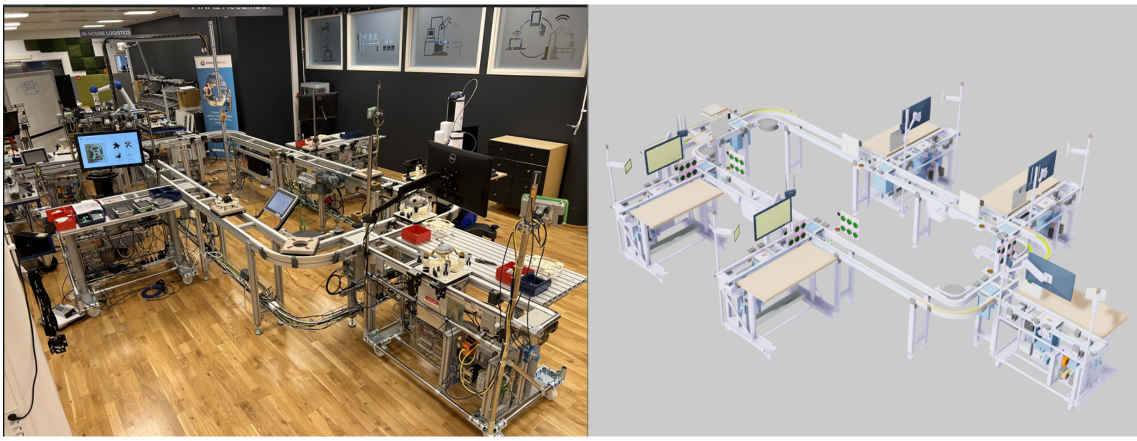
Figure 3.1: Adopted research methodology by authors.

A literature review was performed to get a basic understanding of the underlying concepts that provide the foundation for a DT enabled by VR. With that knowledge, research questions were established to guide the work together with specified objectives for clarification of the work process. During the domain analysis and the deployment of the DT, continuous descriptive research was performed as new concepts emerged. The DT software was explored with the support of tutorials and software experts, while the construction of the IoT architecture was executed by an industry expert. The different processes of the assembly line in the lab-scale drone factory were also studied for a better understanding of the physical system and to gain domain expertise. A qualitative study was performed on the different elements of the IoT architecture for a fuller understanding of the subject, which resulted in a use case design for real-time connectivity.

The use case was based on the ISO 23247 framework to provide an adaptable framework, which can be implemented in different types of use cases to encourage practical implementations. Together with the produced framework, a proof-of-concept use case was designed, to prove that the behaviour of the simulation model mimics the physical system. A table displaying potential business values connected to practical examples was composed, connecting potential business values to corresponding benefits, as a human-centric approach to have better interaction, accessibility and cognitive ergonomics. Following the stated research methodology, a discussion was performed to evaluate the results, ending with conclusions and recommendations for future work.

3.2 Description of Lab-scale Drone Factory

The physical system described in this thesis is implemented at the SII lab in Lindholmen, Gothenburg, which serves as a platform for research, training, and the demonstration of smart industrial production in the context of Industry 4.0 and digital transformation. The lab-scale drone factory infrastructure includes a production line designed for drone assembly, where pallets are used to transport the drones on a conveyor belt. Figure 3.2 displays the real system positioned next to the simulation model, where the conveyor belt connects six branch assembly stations, including a buffer, and an Autonomous Mobile Robot (AMR) transports finished products to a different buffer. Additionally, the lab employs in-house logistics to manage the transformation of raw materials and products, both internally and externally, through the main conveyor belt [37].



(a) SII Lab Real System

(b) Emulate3d Virtual Model

Figure 3.2: Real and Virtual systems of the smart production system

The lab-scale drone factory is controlled by Programmable Logic Controllers (PLCs), with I/O (Input/Output) units distributed across each station, which in this case represents the sensors and actuators of the physical system. All sensors and actuators utilised in stations 2-5 in the lab-scale drone factory are presented in Figure 3.3 [13].

Sensors are strategically placed at each station to detect the arrival of pallets, whereas the pallets are equipped with RFID (Radio Frequency Identification) tags for identification of products. Specifically, the docking station's I/O setup includes two sensors for pallet sensing and another two for monitoring elevator transfers, facilitating the vertical movement of pallets between the main conveyor and the workstation. Additionally, there is a sensor dedicated to managing the queue stop, as well as a sensor identifying the table height as the stations are adjustable to provide an ergonomic environment for operators.

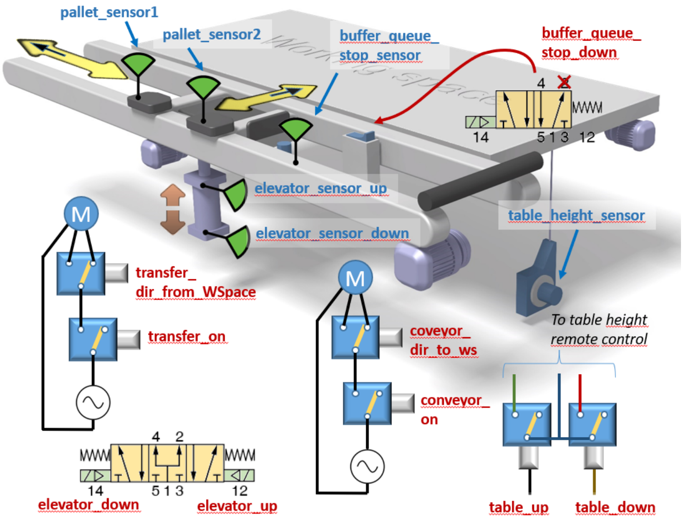


Figure 3.3: Work station I/O Functions with sensors.

3.3 Adopted ISO 23247 Standard Framework For Developing Digital Twins

In this section, the adopted framework for implementing a DT with real-time connectivity is described, based on the ISO 23247 standard [30], to support the connectivity between the physical system, the simulation model, and VR for human-centric interaction. The framework comprises four main parts: (1) Overview and General Principles, which define the physical systems as Observable Manufacturing Elements (OMEs) that need to be twinned; (2) Reference Architecture, which consists of four main domains: OME Domain, Data Collection and Device Control Domain, Core (DT) Domain, and User Domain; (3) Digital Representation, which describes the basic information attributes for typical OMEs, including both static and dynamic information; (4) Information Exchange, which outlines the technical requirements for the exchange of information between entities within the framework. These components provide guidelines for defining the scope and objectives, setting simulation model requirements, implementing a generic reference architecture, and supporting information synchronization between a DT and its physical counterpart [30].

3.4 Virtual Reality Integrated Simulation Solution

Emulate3D (Rockwell Automation, Milwaukee, USA) is a CAD software that was utilised for constructing the simulation model of the lab-scale drone factory. The software includes a library (Emulate3D Package Explorer) of built-in catalogues and pre-modelled components that feature manufacturing equipment components such as conveyors, robots, loads, stairs and walls. The drone product CAD files were imported and the aspects are automatically added. Together with functions such as sensors and buttons, the virtual model can be used for simulation, emulation or demonstration, allowing users to test the connectivity in VR with the HTC VIVE device to enable human-centric interaction.

Furthermore, the simulation software integrates with various communication protocols to facilitate connectivity with IoT devices and platforms enabling real-time data exchange and integration with IoT-enabled systems, with communication languages such as Siemens, CODESYS, Allen Bradley, and OPC UA protocols. Using Tags to represent the physical system's I/O points, Emulate3D's tags are defined in the IO Browser, which displays currently loaded tags, their definition and binding, and connects the tags to the controller via a Tag Server. To ensure the effectiveness of the simulation, simple representations of physical objects should be implemented, together with a reduction of unnecessary physical properties.

Additionally, the real system controlled by PLCs as mentioned in the previous section, parallels the control of the simulation model via a function known as Flow Control. This function allows the users to manage the entities of the simulation model similarly to how the PLC allows the user to control the physical system. The logic behind Flow Control can be implemented using various scripting languages or through a function called Quick Logic in Emulate3D. Quick Logic simplifies virtual model control by allowing users to utilize pre-built functions with minimal coding, simplifying the programming process and making it ideal for quickly implementing logic control. In the Appendix, Figures A.9, A.1, A.6, A.5 and A.8 illustrate various features of Emulate3D software. These include the quick logic window, catalogues, IO browser, properties window, and other functionalities.

3.5 Construction of IoT Architecture

This thesis project primarily focuses on part two of the ISO 23247 standard to support the conception of connectivity, as the excluded parts were completed before implementation. This section will explore the construction of IoT architecture through a detailed examination of its key components. The architecture is typically structured into several layers, each with distinct functions represented in two data models.

3.5.1 IoT Platform and Description of Data Model Components

The IoT platform Thingworx (PTC, Boston, USA), is a licensed enterprise solution which enables connectivity using a modular approach for establishing the corresponding data model to provide feasible scalability. Data is collected, stored and visualized by using the Thingworx Foundation Server, and applications are built with Things, Thing Templates and Thing Shapes, where an example of a data model is conceptualised in Figure 3.4.

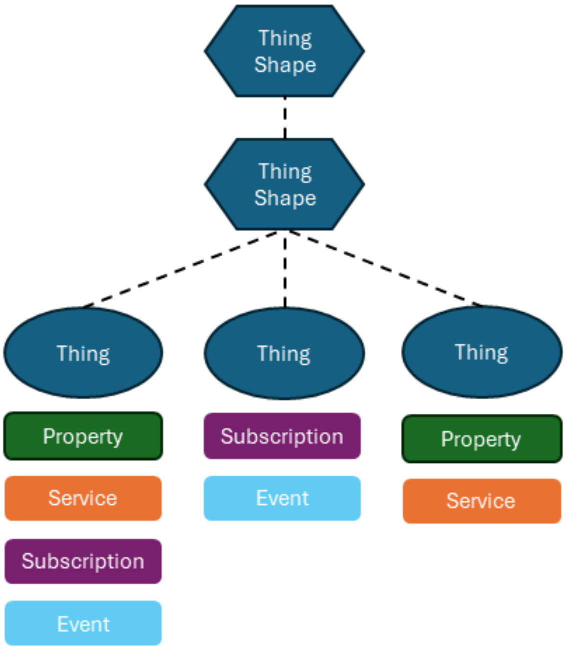


Figure 3.4: Example of a data model and its components within Thingworx.

A Thing represents physical devices, products, systems, processes, assets and people, which is then connected to the simulation model. It is based on a Thing Template that determines a set of Properties (green) and Services (orange), providing the possibility of duplicating Things without constructing them anew. The Thing Shape describes the relations between items using Services, Properties, Events (blue), and Subscriptions (purple), where Thing Templates can inherit Properties and business logic. When a modification occurs in a Thing Shape, the same modification will appear in the connected Thing Template and Thing, providing scalable maintenance and updates to the IoT platform [5].

3.5.2 Data Model Development Steps

To replicate the simulation model in the IoT platform, a data model is constructed following the three steps provided by [5] as seen in Figure 3.5. The first step evaluates the users' requirements, divided into functionality and information, where functionality regards what the user needs to do. This translates to Services and Subscriptions in the IoT platform, together with what data and Properties need to be collected from the physical system. The second step evaluates what parts of the physical system need to be connected, which translates to Things in Thingworx. The selection of Things is based on the previous users' requirements and is aligned with available data and functionality. The recommended next step is to use a Thing-Component matrix, where the Things are in the rows, and the components in the columns, and the Things can be grouped into a Thing Template or Thing Shape, which is done in the third step. The largest group will become the base for a Thing Template, and depending if there is an overlap or not between the other groups, they will form a base for a Thing Shape or a Thing Template.

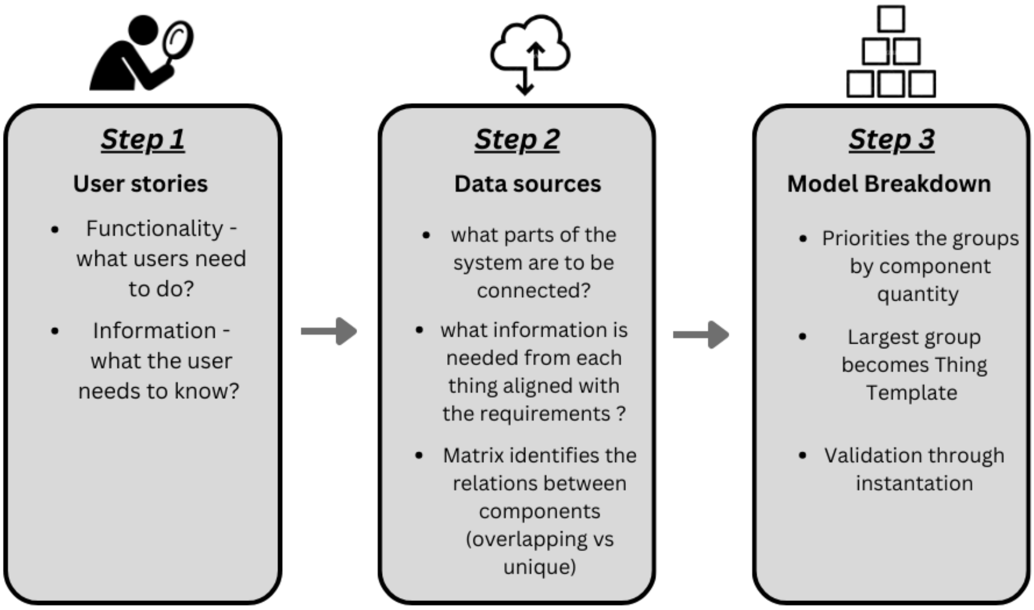


Figure 3.5: Three first steps related to the project for the construction of a data model for an IoT platform [5].

3.5.3 Middleware Component

An important part of the IoT architecture in this thesis is a middleware called Kepware, which is located between the IoT platform and the simulation software. Due to its position in the operation network and not existing within devices, the transferred data can be compromised and it becomes a security issue [47]. Kepware's solution enables encrypted communication and a limited amount of traffic between the different layers of firewalls in the operations network. The setup ensures few openings in the pipelines within the firewalls, limiting the access control while facilitating remote management and configuration of connected devices within the factory's network. As OPC UA is an industry-standard communication protocol [48], and is compatible with Kepware, the middleware can also act as an OPC UA server providing real-time and bi-directional communications between Kepware and the simulation model. For the communication between Kepware and the real system, CODESYS is utilised, which is an automation software for controlling and providing access to PLCs [49]. It is directly connected to Kepware over Ethernet, which is permissible as it is connected to a Local Network Area and will not affect the security of communications.

4

Results

In this section, results are presented following the completion of objectives with the reference architecture based on ISO 23247, presentation of the VR simulation model, description of the integration of IoT platform and simulation model, the connectivity realised with the help of a proof-of-concept use case, and lastly a description of the proven benefits related to a DT enabled by VR in addition to a table describing the potential business value with correlating practical use case examples. In terms of the focus of this proof-of-concept use case, is the operation phase in terms of the lifecycle perspective. It could also easily be applied to the design phase as in virtual commissioning, or for the maintenance phase, although implementing AI analysis is beneficial as it aids in evaluating machine health, for preventive maintenance for instance, or exploration of what-if scenarios [37].

4.1 Reference Architecture Framework Instantiated Based on ISO 23247

As a result, Figure 4.1 shows the instantiated functional view of ISO 23247 reference architecture for the lab-scale drone factory DT implementation. Each domain comprises a logical group of tasks and functions performed by the functional entities (FEs). The OMEs are the physical elements, where data are collected from sources such as CAD files, sensors, and PLCs. The core DT entity manages the simulation modelling, VR modelling, connectivity, synchronization, interoperability, etc. as described in section 3, where the lab-scale drone factory DT performs real-time monitoring and PLC control. User interfaces provided by the user entity enable interaction with the core entity, with VR controllers and the ThingWorx IoT platform for instance, representing the user entity in this use case. The reference architecture supports the development of DTs by displaying the elements vital for the integration and showcasing the interconnectivity by only including parts relevant to this thesis.

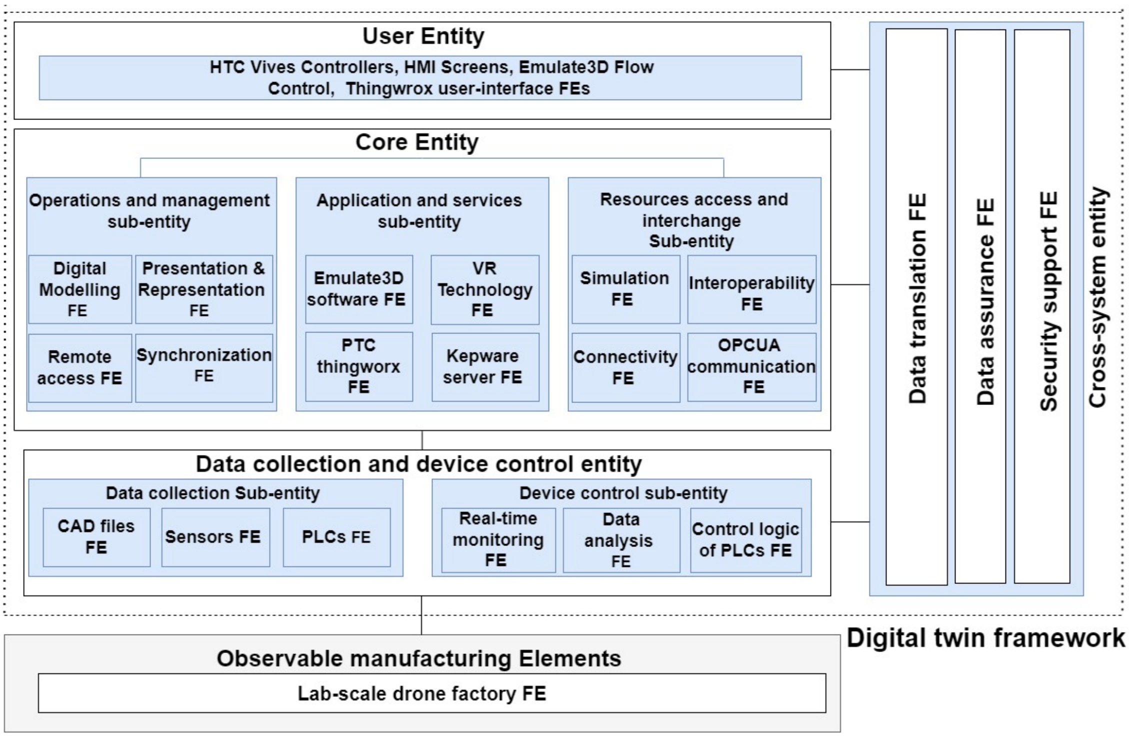


Figure 4.1: Functional view of the instantiated reference architecture (Shao et al. 2021)

4.2 Virtual Reality integrated Simulation Model

The VR functionality is embedded in the Emulate3D software to stream the virtual system's human perspective, which is visualised in Figure 4.2. The functions are the basis for further applications such as virtual operator training and commissioning. The interactions are pre-edited in the desktop view, with pallets, drones, and kits functioning as interactable, grabbable and with gravity physics properties. Then by enabling the button in the VR scene and PLC control system of the physical world, the virtual control is enabled and can be accessed directly from the virtual scene with a headset. To ensure an effective working model, the following adapted best practices are recommended [50]:

- Scripting should focus on making the model correctly in response to PLC signals
- Graphically detailed modeled should be avoided if possible
- If graphically detailed objects are needed, they should be placed in a layer that can be switched off to gain performance
- Simple representations of model hardware are recommended to improve performance
- Use of physics should only be applied where required

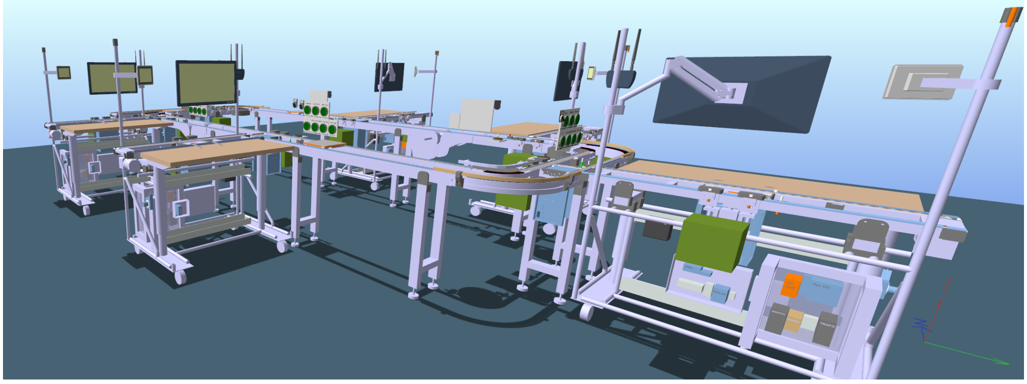


Figure 4.2: Human perspective in VR to control the DT system.

For real-time synchronisation, all sensors are connected with Tags to their data model counterparts in the Kepware server. Figure 4.3 visualises the comparison of Emulate3D's Flow Control (left) and the logic from the PLCs (right), where the Flow Control was constructed to mimic the PLCs as much as possible. This ensures that the simulation model and the physical system operate similarly, facilitating a better understanding of the different processes and the ability to troubleshoot various processes.

```
procedure MainProcedure sender
  set my PB_ChainMotor . ButtonPressed = false
  set my QstopDown . Activate = false
  set my ElevatorDown . Activate = true
  set my ElevatorUp . Activate = false
  set my ElevatorConveyor . State = visual "0"
  set my DSElevatorUp . Activate = false
  set my DSElevatorDown . Activate = true
  set my DSElevatorConveyor . State = visual "0"
  set my Mission = "0"
  wait 0,1 secs
  launch sequence
    forever
    wait until my PB_ChainMotor . ButtonPressed == true changes
  launch sequence
    forever
  forever
    wait 0,2 secs
    if my PB_1 PassDS . ButtonPressed and my Mission == int "0"
    if my PB_5 ElevatorDown . ButtonPressed and my Mission == int "0"
    if my PB_2 MCToWS . ButtonPressed and my Mission == int "0"
```

```

GVL_WS1_IO.buffer_queue_stop_down := FALSE;
GVL_WS1_IO.conveyor_dir_to_WStation :=FALSE;
GVL_WS1_IO.coveyor_on := FALSE;
GVL_WS1_IO.elevator_down := FALSE;
GVL_WS1_IO.elevator_up := FALSE;
GVL_WS1_IO.transfer_dir_from_WSpace := FALSE;
GVL_WS1_IO.transfer_on := FALSE;

rfid_TempElevator:= ''; //Local Tag
GVL_WS1.Mission:=0;
GVL_WS1.myMission:= 0;

DS_to_Elev:= FALSE;
WS_to_Elev:= FALSE;
BU_to_Elev:= FALSE;
Elev_to_DS:= FALSE;
Elev_to_WS:= FALSE;
Elev_To_Buff := FALSE;
```

(a) Flow control code

(b) PLC code

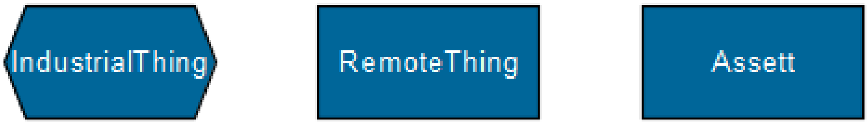
Figure 4.3: Comparison of the Flow control in Emulate3D and PLC code.

4.3 Deployed IoT architecture

To ensure real-time connectivity between the real system and simulation model, data models need to be in place in the IoT platform with applied rules which are needed for practical reasons, for example as in the control of available missions for a docking station. The IoT platform can thus perform different types of tasks with a high level of complexity, such as the proposed future purposes in predictive maintenance, analysis, monitoring, control and optimization. The provided data models have been separated into two parts and simplified to supply a foundation for understanding the concept of the models related to the DT. All subscriptions, properties, events and services are not included, nor the scripting, to facilitate more explanatory models with a focus on the thought process behind them, rather than complex and overly detailed models.

4.3.1 Data models for the Digital Twin and Requests

Both models have three components in common, which are the IndustrialThing Shape, the RemoteThing Template, and the Asset Template, represented in Figure 4.4. The IndustrialThing provides connectivity between Thingworx and Kepware with the aforementioned Application Key and the URL for the Thingworx Foundation Server among other procedures. The RemoteThing is used to bind an industrial tag to Thingworx, which will provide the IoT platform with data from the connected sensors and actuators [51]. Its property, isConnected, verifies the connection, and lastConnection stores previous connections. The Asset Template holds a collection of shared attributes used by several Things, and due to its position high up in the IoT hierarchy, it can be easily accessed and distributed by other databases as well, which is a common industry practice. The property isVirtual is set to true when a panel is needed to synchronise with Emulate3D's buttons as in this case, whereas the property and subscription assetID identifies the different applied attributes and their respective structures.



(a) IndustrialThing Shape (b) RemoteThing Template (c) Asset Template

Figure 4.4: Example of a the common elements of the data models.

The DT data model for the DT can be seen in Figure 4.5 and depicts the events following Button2 being activated. The PanelThing models all Panels, whereas the Thing Shape PanelTS has the property for Button2. This property is connected to the queue stop sensor in the lab-scale drone factory as well as to a tag in Emulate3D. The connectedTo property indicates which location/PLC it is connected to, and when the button is pressed in one of the workstations the service setButton2true will be activated and the subscription button2changed will be set off. The OrchestrationThing will inherit this update and the service MissionRequest will be activated.

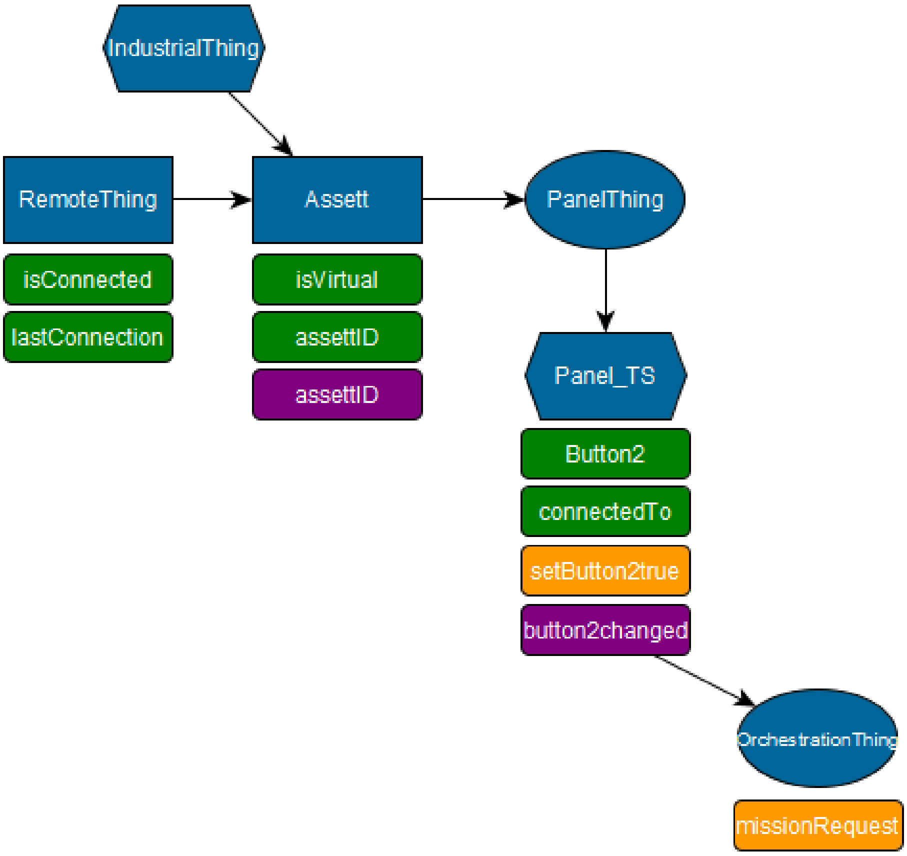


Figure 4.5: Example of a data model for the digital twin.

The data model for requests is depicted in Figure 4.6 and shows how docking station 5 receives a mission request. The DockingStation template holds common values for different docking stations, whereas the DS5 Thing inherits these values. The status of available missions is identified in the avalableMissions property in the LocationTS Thing Shape, and if the mission is available, the requested mission is run with the help of the RunMissionX service. The OrchestrationThing will then perform the requested mission with the help of the callMissionThing service.

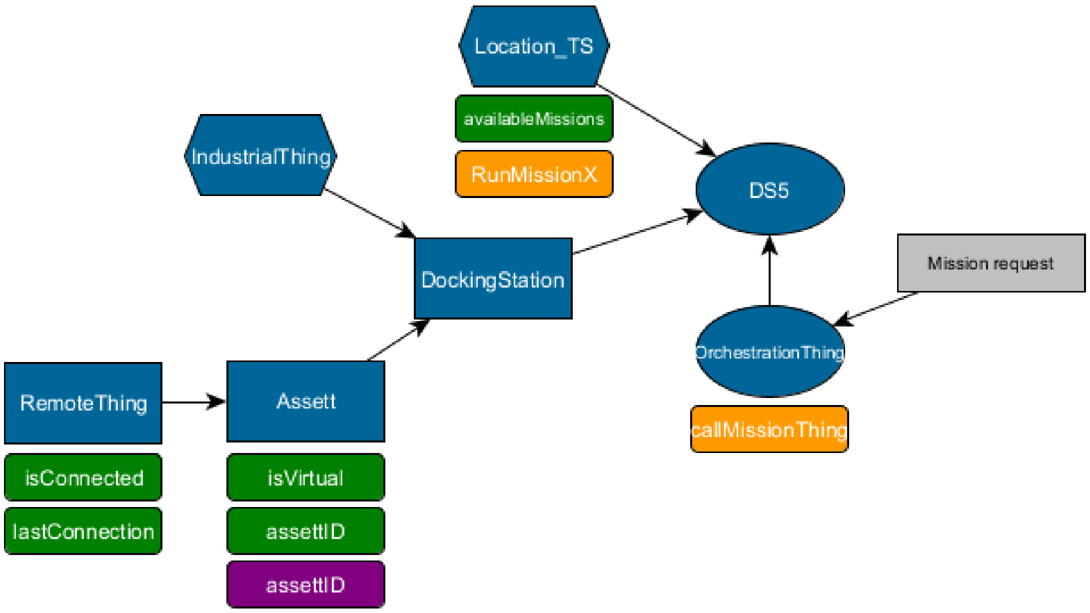


Figure 4.6: Example of a request data model.

4.3.2 Connectivity and Communication Protocols for Server and Client

To connect the deployed IoT architecture to Kepware and subsequently to Emulate3D, Kepware's embedded OPC UA server is used to connect to the provided OPC UA client in Emulate3D. This enables a client-server architecture while providing secure and easy data transfers, and in combination with the port number, connects the client to the correct service in the server. Tags representing sensors or actuators are created in the Kepware OPC UA server, which is then visible to the client, and Emulate3D's tags can then be mapped to the OPC UA client's tags. The client can read what is defined in the server, enabling it to read and write to tags.

Figure 4.7 visualises the structure for communications between Kepware's OPC UA server and Emulate3D's host client. The green arrows indicate the communications, while the orange arrow represents how a request is made and transferred to the physical system.

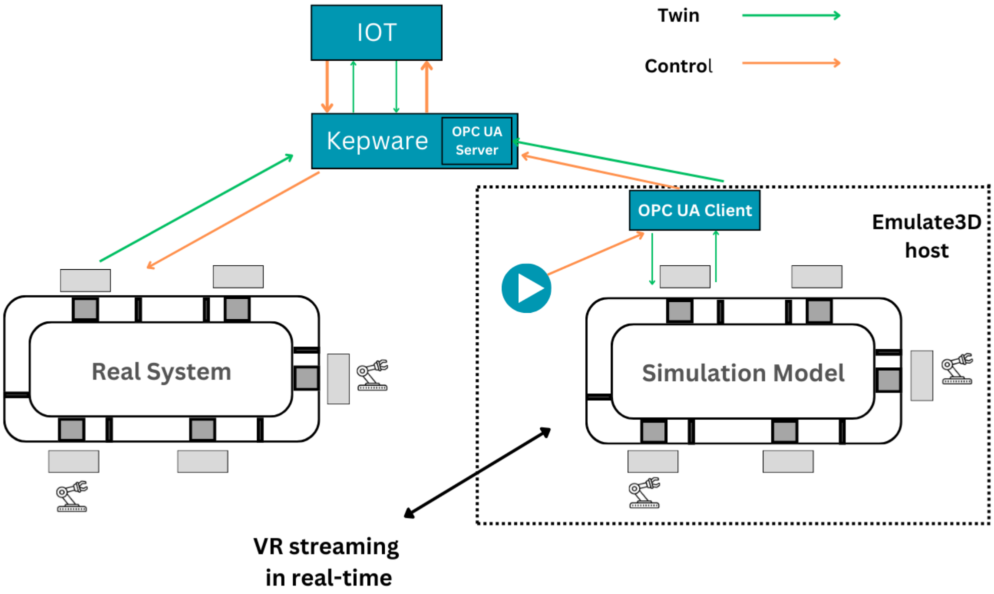


Figure 4.7: Communication between the real system and simulation software.

As the real system serves as the master system, the simulation model initiates a mission by placing a request. The request is sent through the Kepware server with the help of the communication standard OPC UA. Consequently, the request is delivered to Thingworx, which checks if the mission is available, and sends it to the correct station in the real system through CODESYS, which has the PLCs directly connected to the server. The real system returns the confirmation to the simulation model before executing the mission. However, with the selected configurations, the communication between the IoT system and the simulation model results in approximately a one-second latency.

4.4 Proof of Concept of Connectivity Between IoT Platform and Digital Twin Software

The proof of concept use case is presented in Table 4.1, which describes the background for the use case, the objectives and a short description of the demonstrated connectivity. The use case was designed to showcase that the behaviour of the physical and VR simulation systems correspond when selecting a mission by pressing a push button. The table is based on ISO 23247, where the use case has been identified to have a Technology Readiness Level (TRL) of 7 on a scale of one to nine. TRL 7 is defined as a "Technology prototype demonstrated in an operational environment" according to [52], indicating that the technology is functioning in real operating environments, and the technological performance is measured against relevant requirements [53], which in this case is the level of synchronization accuracy when comparing simulation model to the real system.

Table 4.1: Proof of concept use case for connectivity.

ID	SII lab Scale Drone Factory
Use case name	Connectivity between IoT and simulation software
Application field	Smart Manufacturing
Cycle stage(s)/phase(s) coverage	Production
Status	TRL 7 Demonstration in representative environment
Scope	Perform a real-time connectivity in DT
Initial (Problem) Situation	Within the domain of DT frameworks, a fundamental challenge lies in establishing connectivity between the virtual and physical systems. In this context, connectivity refers to the communication protocol enabling synchronous interaction between a virtual model and its physical counterpart. The goal is to facilitate real-time control and movements of the physical entities while ensuring that the DT accurately replicates these actions. The problem is to address how this data connection operates simulation-based DT and the physical system (lab-scale drone factory) ensuring a connection capable of bidirectional data transfer.
Objectives	Implement the real-time connectivity demonstrator in a physical system
Short description	To demonstrate the developed connectivity, missions from PLCs have been virtually created in Emulate3D, represented as push buttons. The logic mimics the real system's progressions. The selected mission is Pass Docking Station, where the user can place the request either in the simulation software, at the IoT platform or directly with the HMI screens belonging to the real system. The blocked drone pallet can then pass the docking station, where the mission is replicated in the simulation model in real time.
Stakeholders	Manufacturing shop floor personnel, management, researchers
Key technologies	Automation, data analytics, simulation, VR, IoT

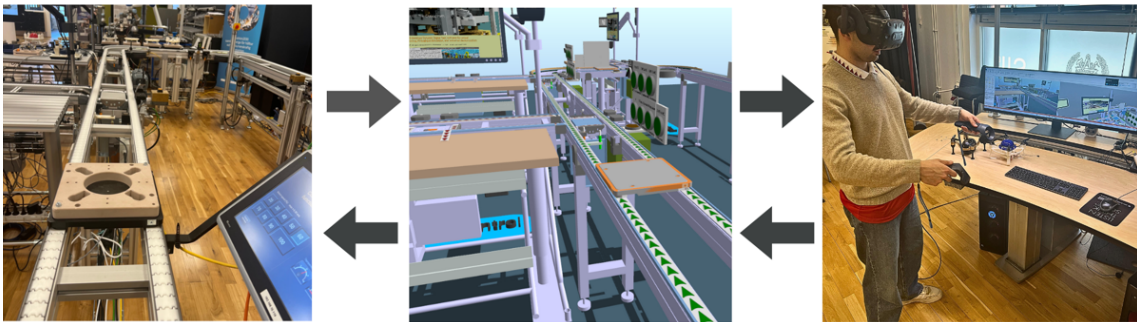
The selected mission for the use case will be to request the drone pallet to pass a docking station. The sensor that hinders the passage will then be deactivated and the pallet can proceed to the next station. To make this request, the user can either use the HTC Vive headset and controllers to virtually make the request by pressing a connected virtual push button, placing the request within Thingworx's user interface, or directly communicating with the PLC through the HMI screen. The objective is to ultimately have the simulated pallet mimic the behavior of the physical pallet, in terms of both speed and position.

Furthermore, the proof-of-concept use case establishes a real-time connected DT where communication and control are bi-directional, with future possible applications such as remote control and monitoring with VR accessibility, which could be potential architecture to support early fault detection, virtual commissioning, training operators, optimisation of production times and throughput, and AI-assisted analysis. VR is integrated into the system by choosing the simulation software that supplies both the PLC protocol and VR streaming function and has been regarded as the key to making the VR-integrated DT successful.

4.5 Verification and Validation of the Digital Twin

As a final step, the deployed DT is verified in terms of the level of operability and then validated by analysing if it has fulfilled its purpose [54], which in this case is to have operative push buttons (both real and virtual) that can be used to control both the simulation model and the real system. To verify the behaviour of the two systems, several verification methods were performed.

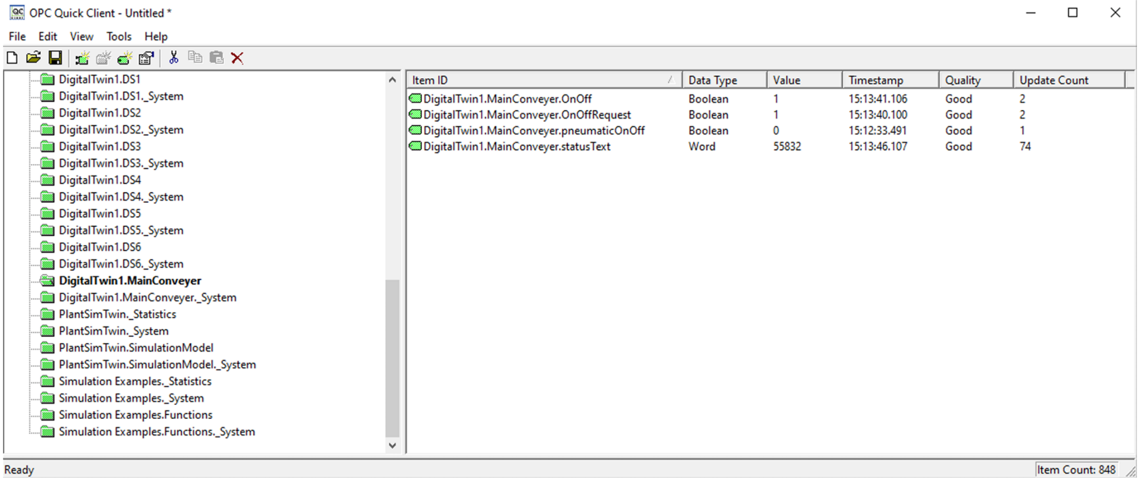
- Depicted in Figure 4.8, the physical system, simulation model and a VR user showcase the real-time connected models and how a user is experiencing the virtual setting while the real system performs the same tasks as the simulation model. A visual inspection of both virtual and real systems was conducted to examine if the systems were synchronised and behaved similarly, as the virtual conveyor belt starts and stops at the same time as the physical conveyor.



(a) Real system (b) Virtual model (c) VR-User

Figure 4.8: Visual inspection of synchronisation between virtual and real system.

- In Figure 4.9, Kepware's OPC Quick Client can be seen, where the connected tags of the DT are presented, where the relevant tags for the use case are MainConveyorOnOff and MainConveyorOnOffRequest. To verify the exchange of data between the physical system and the simulation model, the values from the tags representing the sensors and actuators were inspected for updates. The connectivity was first tested by connecting the conveyor belt's actuator. When the main conveyor is started, the OPC Quick Client's values were updated to ones, meaning that the value is true and the connected actuator is therefor active.



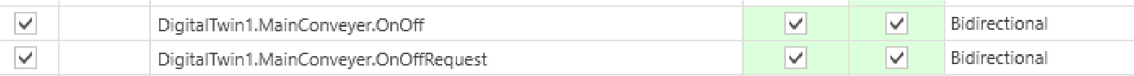
DigitalTwin1.DS1
DigitalTwin1.DS1._System
DigitalTwin1.DS2
DigitalTwin1.DS2._System
DigitalTwin1.DS3
DigitalTwin1.DS3._System
DigitalTwin1.DS4
DigitalTwin1.DS4._System
DigitalTwin1.DS5
DigitalTwin1.DS5._System
DigitalTwin1.DS6
DigitalTwin1.DS6._System
DigitalTwin1.MainConveyer
DigitalTwin1.MainConveyer._System
PlantSimTwin._Statistics
PlantSimTwin._System
PlantSimTwin.SimulationModel
PlantSimTwin.SimulationModel._System
Simulation Examples._Statistics
Simulation Examples._System
Simulation Examples.Functions
Simulation Examples.Functions._System

Item ID	Data Type	Value	Timestamp	Quality	Update Count
DigitalTwin1.MainConveyer.OnOff	Boolean	1	15:13:41.106	Good	2
DigitalTwin1.MainConveyer.OnOffRequest	Boolean	1	15:13:40.100	Good	2
DigitalTwin1.MainConveyer.pneumaticOnOff	Boolean	0	15:12:33.491	Good	1
DigitalTwin1.MainConveyer.statusText	Word	55832	15:13:46.107	Good	74

Ready
Item Count: 848

Figure 4.9: Verification of connectivity within Kepware's OPC Quick Client.

- Illustrated in Figure 4.10, a section of the IO Browser from the simulation software is depicted. Emulate3D's connected conveyor tags are highlighted (green) when activated as the conveyor is running, further verifying the operational connectivity within the simulation software.



☑		DigitalTwin1.MainConveyer.OnOff	☑	☑	Bidirectional
☑		DigitalTwin1.MainConveyer.OnOffRequest	☑	☑	Bidirectional

Figure 4.10: Verification of connectivity within Emulate3D's IO Browser

- Following the same procedure, additional verification was performed, by connecting the Pass Docking Station button and performing visual inspection and data exchange synchronisation. The results show verified connectivity of the deployed DT, ensuring reliable and accurate operations within the DT.

The deployed DT is considered to be validated, as it fulfils the purpose of real-time connectivity between the simulation model and the IoT platform while providing bi-directional communications. The input of real-time data may lead to the need for more complex validation techniques such as testing all properties involved or evaluation of ML-based functions [55], as the DT is dynamic and evolves throughout the system's or a product's life cycle. A DT ultimately leads to a more nuanced and complex analysis of manufacturing systems, resulting in a foundation for decision-making and predictive actions as it is based on current rather than historical data.

4.6 Benefits and Business Values of VR Digital Twins

DTs are associated with several benefits, such as enabling real-time monitoring and control of various manufacturing processes with bi-directional communication, the ability to test and optimize products and processes before implementation, predictive maintenance, virtual commissioning and exploring what-if scenarios. These benefits can provide an increase in efficiency and product quality, and decrease operational costs [56].

When incorporating VR with the deployed DT, the cyber-physical system becomes more human-centric, sustainable and resilient, transforming it from Industry 4.0 to Industry 5.0. The benefits provided by VR are linked to the enhancement of the operator's abilities, such as improving skill levels and shortening staff training, as well as elevating production by improving quality and industry competitiveness while reducing assembly defects [57].

The integration of VR technology within DT has thus a potentially significant impact on enhancing business value in the manufacturing industry, depending on the available technology and its purpose. As shown in Table 4.2, the objective of the table is to describe the potential business values associated with various VR use cases, leading to a systematic discussion of benefits related to their potential business values.

Table 4.2: Business Value of DTs through VR technology with their potential use cases.

Category	**Potential Business values**	**VR Use-Cases**
Quality	• Early prediction and detection of quality trend defects • Control quality escapes and ability to determine when quality issue starts	• Virtual commissioning Digital twin
Operations costs	• Improvement of product design and engineering change execution • Improvement of performance of manufacturing equipment • Reduction of operations and process variability	• Virtual prototyping • Remote controlling • Training operators
New product introduction cost and lead time	• Reduction of time to market for new products • Reduction of overall costs for new product • Improved recognition of long-lead-time components and impact on supply chain	• Scheduling and Routing Digital twin • Robot teaching point through VR controllers
Revenue growth opportunities	• Identification of products ready for upgrade in the field • Improvement of efficiency and cost for servitization	• Customer experience and support. • DT as product life cycle management.

DT through VR can serve as a powerful quality management tool by enabling the prediction and early detection of errors and defects. For instance, the virtual commissioning use case allows businesses to simulate and address potential quality problems before the physical system is implemented. This ensures that quality problems are identified at the virtual stage, thereby improving overall quality control.

Operational cost reduction also has potential business value in the manufacturing industry through VR applications. Use cases such as virtual prototyping and remote controlling allow for more efficient product design and engineering changes. For example, a remote expert can use a 3D representation of a physical asset in a VR environment to check the spatial relationships among components, aiding a local operator in troubleshooting [54]. Additionally, for training operators, VR can shorten the time and cost for a new operator to learn and familiarize themselves with the work instructions and work environment. It provides immersive and interactive training in virtual environments, allowing operators to practice without the risks associated with real-world training [58].

In the context of new product introductions, VR helps reduce time to market and costs by simulating production processes in a virtual environment. This enables businesses to identify and address potential bottlenecks. Moreover, DT technology enabled by VR allows various departments to access the virtual model, facilitating better collaboration. This enables teams to test what-if scenarios and modify product designs in real-time. Revenue growth is further supported by VR's ability to enhance customer experience and support decision-making through engaging customers, offering virtual demonstrations, and providing immersive experiences.

5

Discussion

The integration of Thingworx and Emulate3D resulted in a connected DT with real-time data exchange and bi-directional communications and control. VR enabled the user to be fully immersed in the simulation model, providing cognitive support and the ability to remotely monitor and control the lab-scale drone factory. The connectivity was upheld through the OPC UA server embedded in Kepware, together with an OPC UA client in Emulate3D, providing secure and easy communications between the simulation model and the IoT platform, while providing human-centric interaction with the technology.

The results suggest that implementation of DTs in a manufacturing environment is feasible, however for the implementation to be successful, there exists a need for mature DT-related technology along with domain and software experts. The ISO 23247 framework ensured a standardised way of describing the DT architecture, further promoting correct usage of definitions and providing guidelines for the development of the DT. The provided IoT solutions removed several common implementation obstacles, such as platform connections, hardware, collection and collection of data and security issues. The utilization of VR provided by Emulate3D provided accessible ways of verifying the connectivity and the model performance by comparison with the behaviour of the physical system.

5.1 Reference Architecture Based on ISO 23247

An initial objective of the project was to identify a protocol connection between the simulation software and the IoT platform to establish real-time connectivity with the support of DT standards. Due to the variety of digital twin definitions, inconsistent terminologies, and the lack of a standardized process, relevant standards that provide implementation guidelines can help clarify what a digital twin is and how it can be implemented in the manufacturing industry. This is particularly important for SMEs. In this thesis, the ISO 23247 standard was used to support this integration, as the standard provides a precise definition, framework, and guidelines that help address these challenges.

As mentioned in the methodology chapter, the ISO 23247 DT standard comprises four initial main parts: (1) Overview and General Principles, (2) Reference Architecture, (3) Digital Representation, and (4) Information Exchange. This thesis project focuses on part two of the ISO 23247 standard, supporting the conception of connectivity, as the excluded parts were completed before implementation. However, it is important to note that the ISO 23247 standard is still under development and has not been fully completed, and currently a draft of the standard has been published. The full standard will consist of six parts in total, which has not yet been published. These new parts of the standard can be tailored for specific manufacturing sectors, such as additive manufacturing, by introducing new functional entities or replacing existing ones to meet the requirements. Ultimately, the framework standard needs to be updated to incorporate adding additional capabilities to address new problems and various use cases.

5.2 Simulation Model

The simulation model replicates the real system in a virtual environment, offering a dynamic and immersive experience for the user as it simulates the real system in real time. However, one interesting finding is that the RFID tags currently have not yet been incorporated into the DT, meaning that the two systems are not fully synchronised. It is recommended for future research to develop a system that updates the pallet's position in real time while accounting for communication latency. To accurately simulate the pallet positions on the conveyor belt in the lab-scale drone factory, these RFID tags need to be placed throughout the system. As it stands, the simulation model can only detect the pallets when they are at the workstations as the sensors are placed at these stations, and not while they are moving on the conveyor belt. Another important finding is that the real system is controlled by PLCs, while the simulation model is controlled by a flow control mechanism, as mentioned in the methodology chapter. This flow control acts as a virtual PLC, so for the two systems to be fully synchronised, all sensors and actuators need to be connected through the IoT platform to the simulation software.

In addition, Emulate3D software can be used in different ways: through a computer, via wearable tools such as VR headsets, and potentially other interfaces. The maturity of technologies for VR, Augmented reality (AR) and extended reality (XR) within the gaming and video entertainment industry can now be leveraged to enhance the visualization experience in the manufacturing sector. In this thesis, HTC Vive controllers were used in integration with the simulation software. The VR sets provide a fully immersive experience, allowing users to feel as though they are physically present in the manufacturing environment. However, for manual assembly tasks that require fine motor skills, such as fastening nuts and bolts, glove controllers might be a better option, providing natural hand movements.

5.3 Connectivity Between Simulation Model and IoT Platform

As discussed by [59], the inherited latency due to existing configuration affects the real-time data updates, but depending on the context, the configurations might need to be altered. For the proof-of-concept use case, monitoring and control will be the main applications for the DT, and the latency must then be minimised to ensure synchronisation between the real system and the simulation model to not affect the operations.

Within the IoT system, more levels of integration are left for further improving the data models, such as adding more rules with scripting (e.g. adding a Mission Complete property), exploring other types of communication protocols, and adding more layers of Kepware servers in the case of accessing the physical system outside of LAN.

As for a practical point of view for the implementation of a DT for monitoring and control of manual assembly, the security issues and the purpose of the DT should be investigated before deployment. For instance, a moving assembly line controlled remotely can risk the safety of operators if they are within the vicinity when a request is being executed. To ensure the safety of operators, pressure-sensitive mats can be installed blocking control of the assembly line remotely when an operator is standing on it. For this specific use case, the virtual platform should have strict authority requests and should mainly be used as a monitoring system, emergency maintenance support, and remote control system when no operators are working in the workstation area. However, regardless of the risk, implementing DTs correctly in the factory will still be the key component of accelerating the digital transformation of the industry. Other ways of ensuring operator safety could be a motion-detecting camera, or to decrease the speed of the conveyor belt if operators are standing too close.

5.4 DT Through VR Business Values and Industry 5.0

In the context of Industry 5.0, DT enabled by VR technology holds significant business value by enhancing human-centric, sustainable, and resilient manufacturing processes. Real-time connectivity for VR-enabled DTs allows for more personalized and efficient production flows. For instance, VR can quickly and effectively introduce the production line to a new worker or guest, requiring only a minimal amount of time to demonstrate the factory layout, including the production line, conveyor belts, workstations etc. Moreover, VR plays a vital role in operator training by providing immersive views and simulations of real-system counterparts. This allows operators to experience cognitive loads and gain practical experience even before the actual system is built. By continuously upskilling and training employees, VR empowers workers to adapt to changing job roles and acquire new skills.

Moreover, incorporating technologies such as VR adopts a human-centric approach, creating an inclusive and safe working environment. For dangerous tasks, workers can perform them virtually before executing them in the real world. This allows employees to focus on value-adding, creative tasks while dangerous tasks are handled by machines, leading to improved productivity. Technologies such as IoT emphasize the responsible and efficient use of resources in the manufacturing industry. For example, in an IoT connected with a production line, sensors are attached to various components to monitor parameters such as conveyor speed and cycle time. The data collected by these sensors in real time is then analyzed by an IoT server. This server uploads the data into a simulation model, allowing users to experiment with what-if scenarios. By doing so, users can identify and implement optimal solutions for improving efficiency and reducing energy consumption. As a result, companies can optimize resource consumption, reduce waste, and minimize environmental impacts.

To further evaluate its benefits on social sustainability, such as cognitive ergonomics, better decision-making support, and pedagogy in the virtual training, the VR-integrated DT demo should be further developed into a use case and experiment, along with user investigation. The use case shown in this study is to showcase that, following the standardized ISO 23247, the DT case could be enabled in the specific simulation software and physical system, while its benefits and further safety risks are still to be explored, and could be identified as a future study.

6

Conclusion & Future Work

6.1 Conclusion

This project demonstrates how connectivity in dynamic DTs can potentially drive improvements in system operations and decision-making processes, with VR integrated to highlight the human-centric perspective in the technology. It presents a reference architecture for integrating IoT platforms with 3D simulation software based on the ISO 23247 DT Framework. The objectives are to fulfill the current gaps in pragmatic implementation strategies and verification of frameworks, by enabling real-time connectivity between digital and physical systems and to showcase the potential business values and technology benefits of VR. Furthermore, the thesis outlines a methodology for the practical application and standardization of DT connectivity in manufacturing systems, with VR integrated for future human-centric DT scenarios.

6.2 Future Work

As the digital twin connection has not been fully connected and remains incomplete, our project focuses on demonstrating real-time connectivity through two operations: one to turn On/Off the conveyor belt, and the other involving passing through the docking station. Moving forward, future research should consider extending this connectivity across all the operations and connected devices within the lab-scale drone factory. This includes connecting operations from the main conveyor to the work station, vice versa, and any other relevant operations within the drone factory.

There is also room for further progress in testing a DT combined with a Cobot use case for example. Given that the lab-scale drone factory incorporates both manual and automated assembly processes, this use case can be applied to show how automated processes can enhance production and further establishing the benefits of DTs through VR. It can also demonstrate how the VR controllers can be used for creating a path for movement quickly, by utilizing robot teaching points within the VR environment.

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A

Appendix

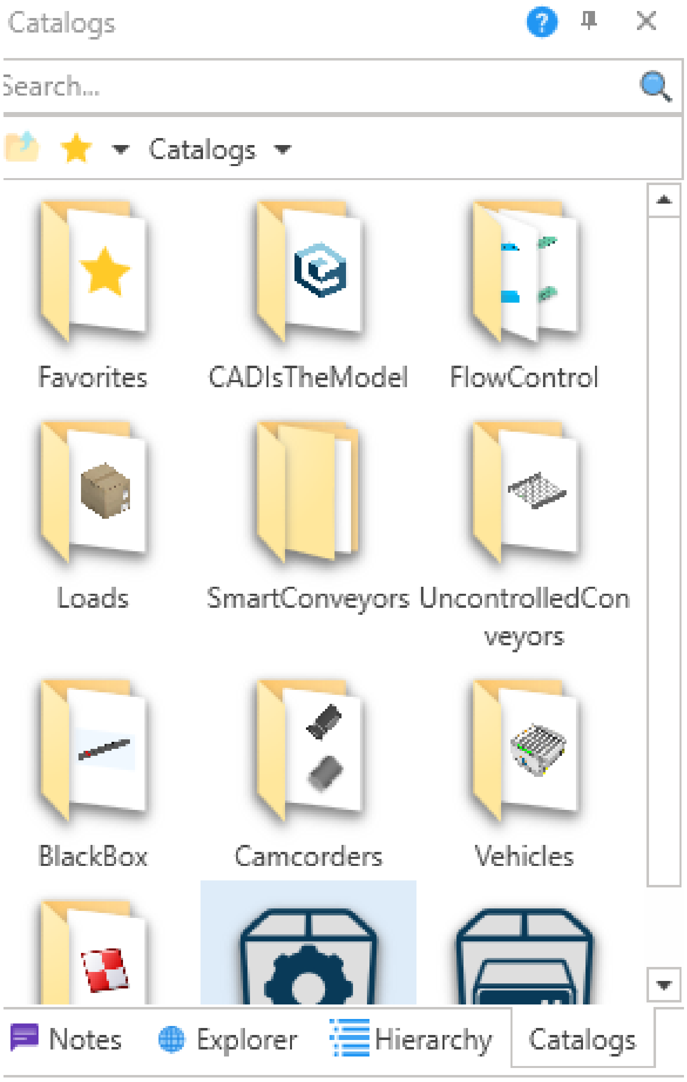


Figure A.1: Catalogs components in Emulate3D

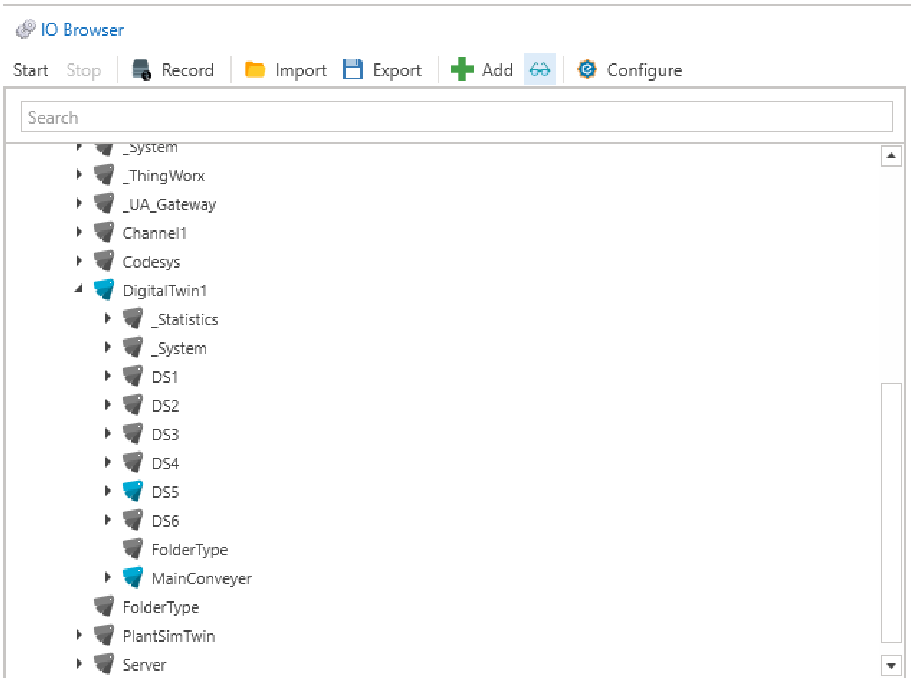


Figure A.2: Uploaded tags in the IO Browser

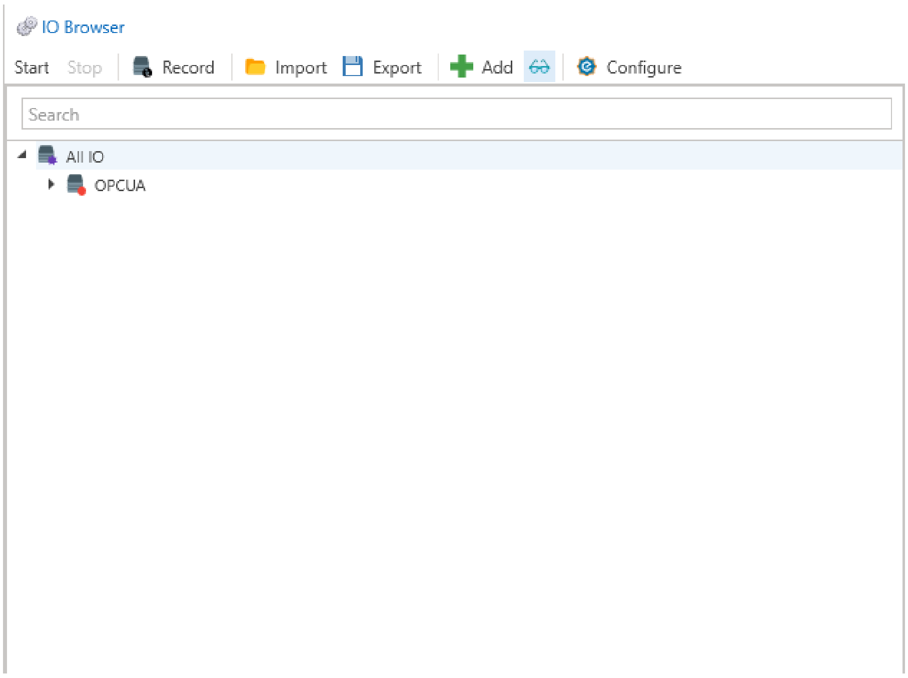


Figure A.3: Connecting Emulate3D through OPC UA

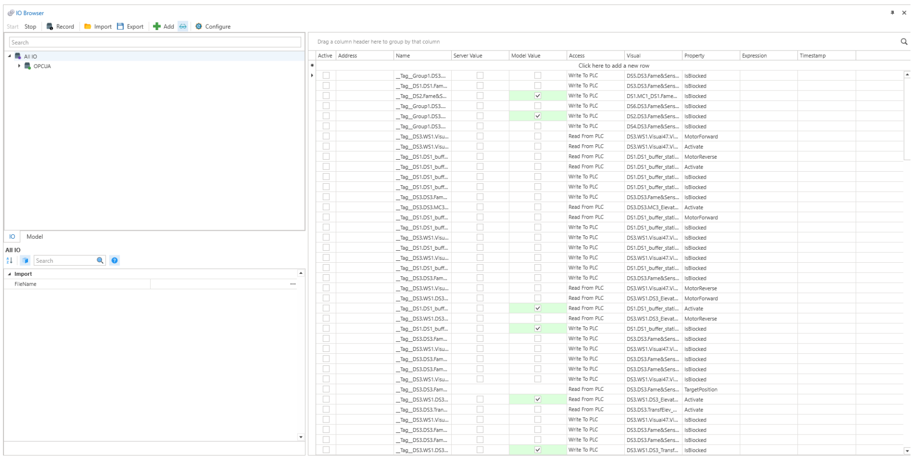
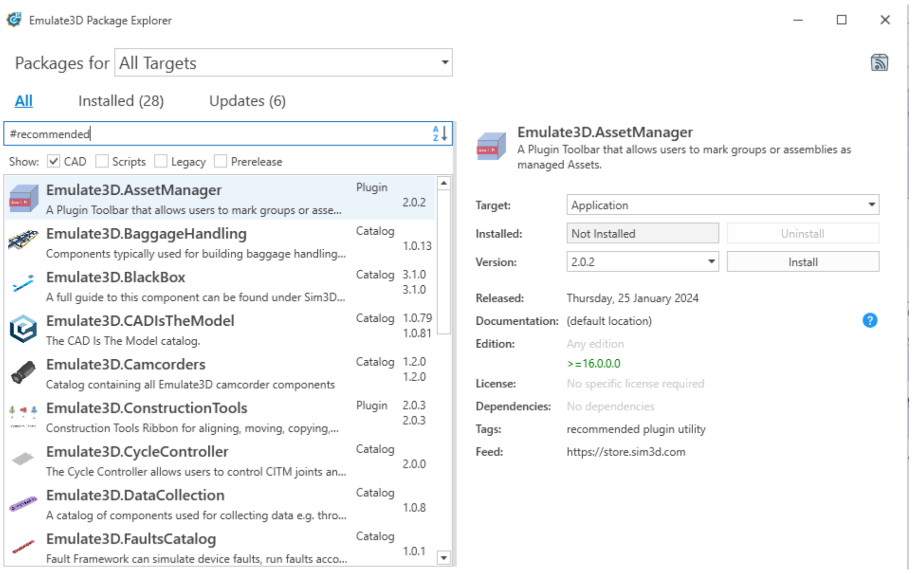


Figure A.4: tags uploaded form Kepware server in Emulate3D IO Browser



Emulate3D Package Explorer

Packages for All Targets

All Installed (28) Updates (6)

#recommended

Show: ☑ CAD ☐ Scripts ☐ Legacy ☐ Prerelease

Emulate3D.AssetManager A Plugin Toolbar that allows users to mark groups or asse...	Plugin	2.0.2
Emulate3D.BaggageHandling Components typically used for building baggage handling...	Catalog	1.0.13
Emulate3D.BlackBox A full guide to this component can be found under Sim3D...	Catalog	3.1.0 3.1.0
Emulate3D.CADIsTheModel The CAD Is The Model catalog.	Catalog	1.0.79 1.0.81
Emulate3D.Camcorders Catalog containing all Emulate3D camcorder components	Catalog	1.2.0 1.2.0
Emulate3D.ConstructionTools Construction Tools Ribbon for aligning, moving, copying,...	Plugin	2.0.3 2.0.3
Emulate3D.CycleController The Cycle Controller allows users to control CITM joints an...	Catalog	2.0.0
Emulate3D.DataCollection A catalog of components used for collecting data e.g. thro...	Catalog	1.0.8
Emulate3D.FaultsCatalog Fault Framework can simulate device faults, run faults acco...	Catalog	1.0.1

Emulate3D.AssetManager
A Plugin Toolbar that allows users to mark groups or assemblies as managed Assets.

Target: Application

Installed: Not Installed

Version: 2.0.2

Released: Thursday, 25 January 2024

Documentation: (default location)

Edition: Any edition
>=16.0.0.0

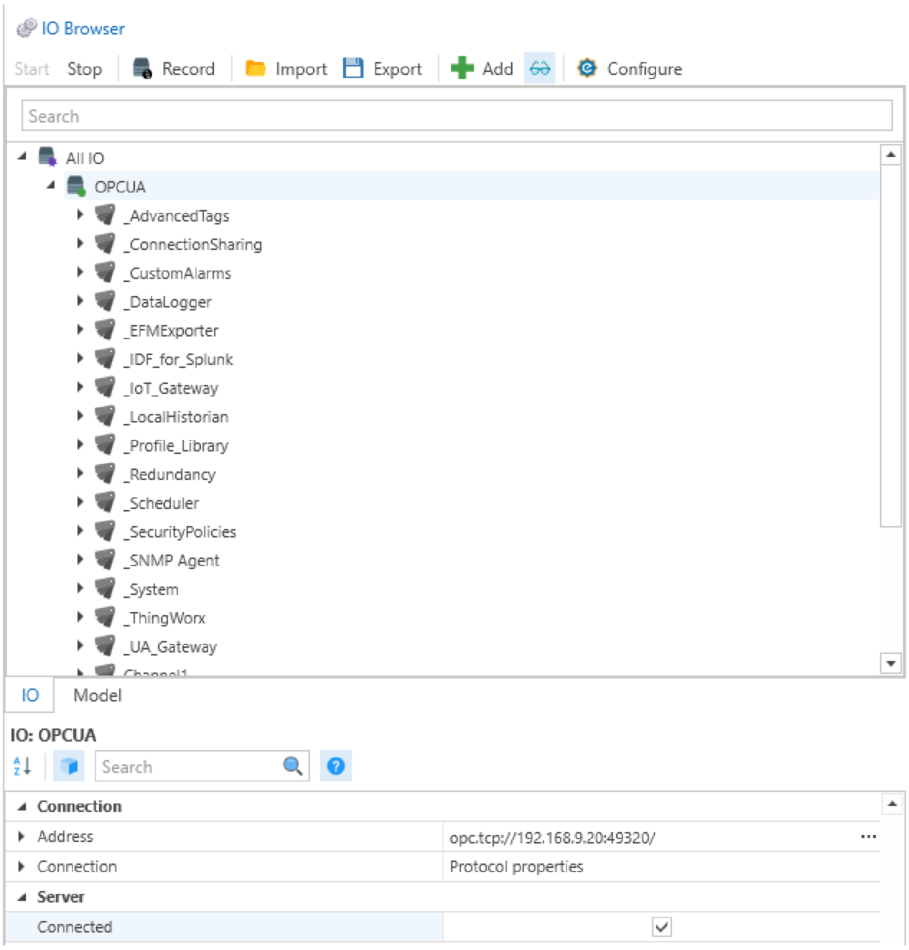
License: No specific license required

Dependencies: No dependencies

Tags: recommended plugin utility

Feed: https://store.sim3d.com

Figure A.5: Emulate3D library



IO: OPCUA

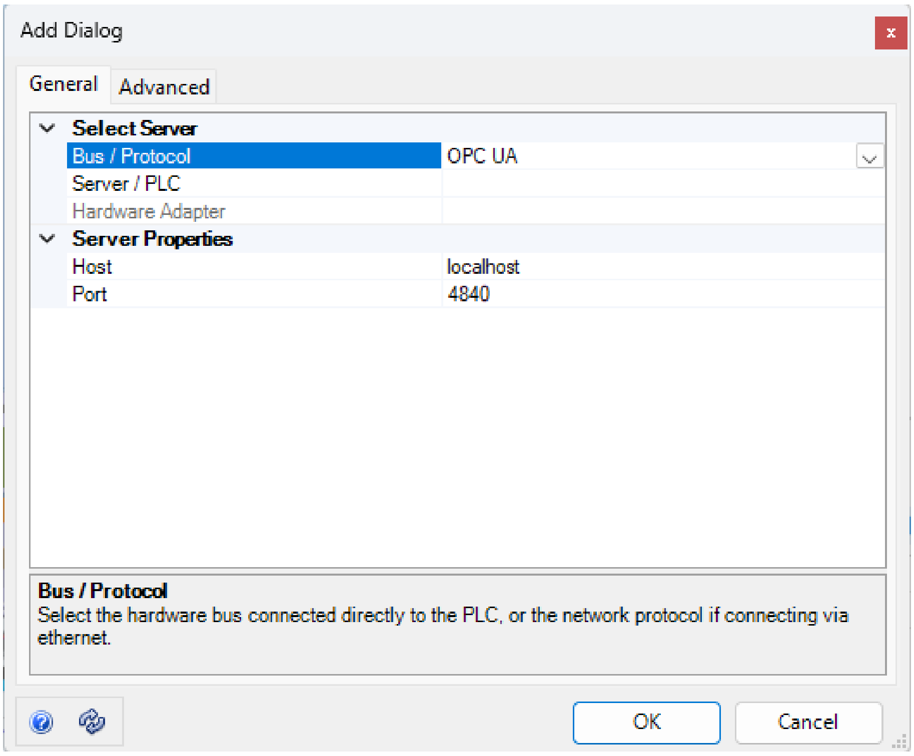
Connection

Address	opc.tcp://192.168.9.20:49320/
Connection	Protocol properties

Server

Connected	☑

Figure A.6: communication starting through OPC UA



Select Server

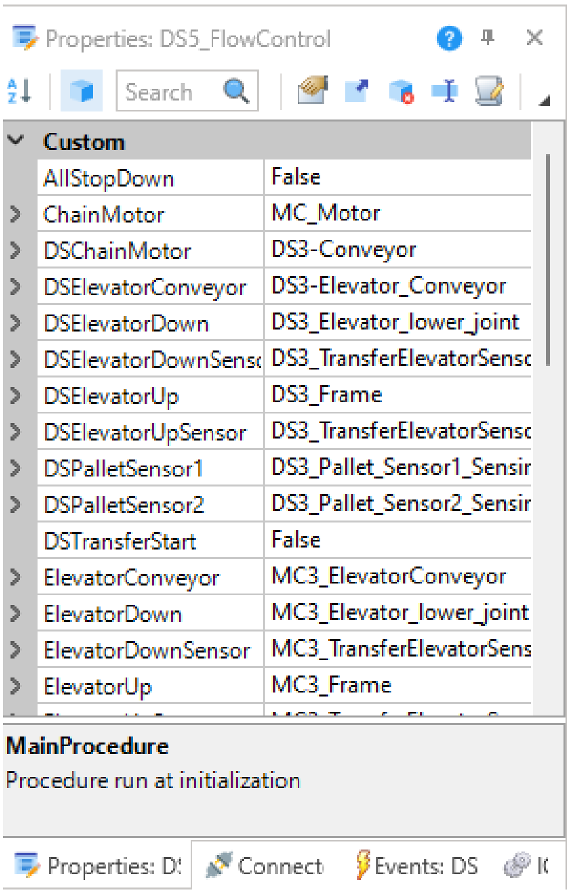
Bus / Protocol	OPC UA
Server / PLC	
Hardware Adapter	

Server Properties

Host	localhost
Port	4840

Bus / Protocol
Select the hardware bus connected directly to the PLC, or the network protocol if connecting via ethernet.

Figure A.7: Emulate3D different protocol connections

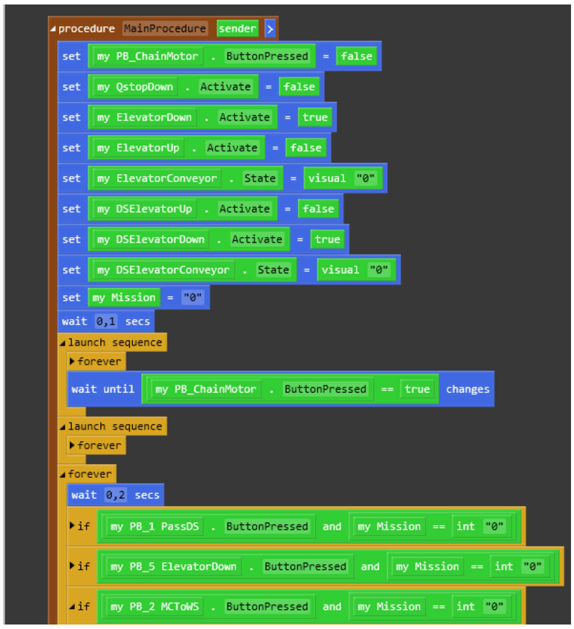


Custom

AllStopDown	False
ChainMotor	MC_Motor
DSChainMotor	DS3-Conveyor
DSElevatorConveyor	DS3-Elevator_Conveyor
DSElevatorDown	DS3_Elevator_lower_joint
DSElevatorDownSensc	DS3_TransferElevatorSensc
DSElevatorUp	DS3_Frame
DSElevatorUpSensor	DS3_TransferElevatorSensc
DSPalletSensor1	DS3_Pallet_Sensor1_Sensir
DSPalletSensor2	DS3_Pallet_Sensor2_Sensir
DSTransferStart	False
ElevatorConveyor	MC3_ElevatorConveyor
ElevatorDown	MC3_Elevator_lower_joint
ElevatorDownSensor	MC3_TransferElevatorSens
ElevatorUp	MC3_Frame

MainProcedure
Procedure run at initialization

Figure A.8: Properties window in Emulate3D



```
procedure MainProcedure sender >
  set my PB_ChainMotor . ButtonPressed = false
  set my QstopDown . Activate = false
  set my ElevatorDown . Activate = true
  set my ElevatorUp . Activate = false
  set my ElevatorConveyor . State = visual "0"
  set my DSElevatorUp . Activate = false
  set my DSElevatorDown . Activate = true
  set my DSElevatorConveyor . State = visual "0"
  set my Mission = "0"
  wait 0,1 secs
  launch sequence
    forever
    wait until my PB_ChainMotor . ButtonPressed == true changes
  launch sequence
    forever
  forever
    wait 0,2 secs
    if my PB_1 PassDS . ButtonPressed and my Mission == int "0"
    if my PB_5 ElevatorDown . ButtonPressed and my Mission == int "0"
    if my PB_2 MCToWS . ButtonPressed and my Mission == int "0"
```

Figure A.9: Quick logic in Emulate3D

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