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Digital Twin & Fleet Monitoring Dashboard

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# Glossary

AMQP - Advanced Message Queuing Protocol

API – Application Programming Interface

AR – Augmented Reality

BDA – Big Data Analytics

BIM – Building Information Modelling

CAD – Computer-Aided Design

CM – Cloud Manufacturing

CoAP - Constrained Application Protocol

CPS – Cyber-Physical Systems

DIAMND – Diagnostics and Monitoring

ERP – Enterprise Resource Planning

FTP – File Transfer Protocol

HTTP – Hypertext Transfer Protocol

IMAP - Internet Message Access Protocol

IoT – Internet of Things

OLE - Object Linking and Embedding

OPC-UA – OLE for Process Control Unified Architecture

PLC – Programmable Logic Controller

PLM – Product Lifecycle Management

POP3 - Post Office Protocol

RFID – Radio Frequency Identification

SMTP - Simple Mail Transfer Protocol

SQL – Structured Query Language

TCP/IP - Transmission Control Protocol/Internet Protocol

UDP - User Datagram Protocol

VR – Virtual Reality

XMPP - Extensible Messaging and Presence Protocol

# Abstract

# Introduction



## Background and Significance of the Study

## Research Objectives

# Literature Review



## Digital Twins



### Origin of Digital Twins.

The concept of the "Digital Twin," which has emerged as a pivotal framework in the realm of engineering and industrial applications, finds its origins in the early 2000s. Dr. Michael Grieves, a scholar at the University of Michigan, is credited with applying and pioneering the foundational ideas behind it (Sjarov et al., 2020). Initially referred to as the "Mirrored Spaces Model," later renamed by NASA’s John Vickers as “digital twin”, the Digital Twin comprises three fundamental components that collectively constitute its essence. These components, seen in Figure 1, consist of the "Real Space," representing the tangible, physical counterpart; the "Virtual Space," serving as the digital replica or simulation of the real-world entity; and the intricate web of connections that interlinks data and information, bridging the gap between the virtual and real products (D’Amico et al., 2019). This innovative framework has since evolved into a versatile and indispensable tool, offering profound insights into various domains, including crane fleet monitoring, where it enables the creation of highly accurate virtual representations of physical assets and facilitates the real-time tracking and analysis of their performance. The developmental trajectory of Digital Twins unfolds across three discernible phases. In its initial instantiation, the digital model lacks the mechanism for automated data exchange between physical and digital entities. Progressing to the second stage, identified as the digital shadow, a paradigm shift is observed with the introduction of automated unidirectional data flow from physical to digital objects. The third and most advanced stage, epitomised by the digital twin, witnesses the establishment of a bidirectional data flow facilitating seamless integration between physical and digital entities (Wang et al., 2020).

A diagram of a space shuttle

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*Figure 1 – Components of a Digital Twin (D’Amico et al., 2019).*

### How do Digital Twins Work?

1. On the physical side, we now collect more
2. and more information about the
3. characteristics of the physical product. We
4. can collect all types of physical
5. measurements from automated quality
6. control stations, such as Coordinate
7. Measuring Machines (CMMs). We can
8. collect the data from the machines that
9. perform operations on the physical part to
10. understand exactly what operations, at
11. what speeds and forces, were applied. For
12. For example, we can collect the torque
13. readings of every bolt that attaches a fuel
14. pump to an engine to ensure that
15. each engine/fuel pump attachment is
16. successfully performed.

Real-world machines are equipped with an assortment of sensors that record critical performance data. These sensors capture information on various aspects of the crane's operations, including parameters such as load capacity, movement, environmental conditions, and more (IBM, n.d.). In the realm of digital twinning for fleet monitoring, the convergence of physical and virtual elements assumes paramount significance. This integration is prominently illustrated through the acquisition of multifaceted physical measurements, derived from the Programmable Logic Controller (PLC) of cranes, which encompass variables such as spatial position and speed of the crane's spreader. These tangible data inputs form the foundation for the construction of a comprehensive digital twin. Furthermore, on the virtual side, the research underpins a substantial augmentation in the depth and breadth of available information. This augmentation is primarily achieved through the incorporation of an extensive array of behavioural characteristics. These attributes, inclusive of various performance parameters, not only facilitate the visual representation of the crane but also empower rigorous testing of its capabilities, ensuring a holistic understanding of its operational dynamics. Although the present investigation emphasises the capacity for virtual testing, it is pertinent to note that for certain applications, the focus may primarily be on generating lightweight virtual models to mirror physical counterparts, with the foremost aim being real-time visualisation of intricate systems, even in cases where comprehensive performance testing may not be feasible or necessary.

### Digital Twin: Use Case Models

The application of Digital Twin technology in crane monitoring and fleet management unveils a realm of profound utility, effectively harnessing the capabilities of conceptualisation, comparison, and collaboration as outlined by Grieves (2014). Conceptualisation, in the context of crane operations, enables a transformative approach to understanding the status and performance of these heavy machinery assets. Unlike conventional data processing, Digital Twins offer the unique advantage of real-time, visual representation, eliminating the need for manual translation of visual information into symbolic data. Through the Digital Twin, operators can simultaneously visualise the physical crane's condition and its virtual counterpart, allowing for a seamless comprehension of crucial data.

Moreover, comparison becomes an indispensable analytical tool in crane and fleet monitoring. The Digital Twin allows for the immediate evaluation of desired operational outcomes against actual results, eliminating the inefficiencies associated with manual data cross-referencing. By overlaying the ideal characteristics and tolerance corridors, the Digital Twin empowers users to swiftly assess whether the cranes and fleet are performing within acceptable parameters, with deviations colour-coded for instant recognition. These comparisons extend to various measurements, including tensile strength, torque readings, and other critical performance metrics, enhancing real-time decision-making.

Collaboration in crane and fleet management takes on a new dimension with the Digital Twin. Traditionally, operational assessments and troubleshooting were confined to a local context. However, the Digital Twin enables a shared conceptualisation that can be accessed and visualised by teams worldwide, transcending geographical boundaries. This global perspective allows stakeholders from various locations to monitor their fleet and compare their performance with fleets across the globe. In the event of an issue in one fleet, the solution can be promptly identified and shared with other fleets, fostering collaborative innovation on a global scale (Grieves, 2014).

In summary, the application of Digital Twins in crane monitoring and fleet management aligns seamlessly with the conceptualisation, comparison, and collaboration framework proposed by Michael Grieves. This technological advancement not only streamlines crane operations but also empowers global teams to collaborate in real-time, driving innovation and efficiency across the fleet management landscape.

### Choosing Unity 3D for Visualisation of Digital Twins

Unity3D serves as the linchpin in the landscape of digital twin development, offering an array of potent features and capabilities meticulously tuned to cater to the specific demands of digital twin applications. At its core, Unity3D excels in data ingestion and optimisation. This powerful technology seamlessly imports data from diverse formats, including BIM (Building Information Modelling) and CAD (Computer-Aided Design). It integrates data from various systems such as PLM (Product Lifecycle Management), ERP (Enterprise Resource Planning), and IoT (Internet of Things). Unity's data preparation tools are nothing short of impressive, facilitating the import and optimisation of over 70 formats. This results in the creation of a unified, real-time representation of physical assets that forms the bedrock of digital twins (Unity, n.d.).

When it comes to flexible and efficient creation tools for digital twins, Unity3D stands out as a global leader. Renowned as the foremost real-time 3D platform worldwide, Unity is further enhanced by a suite of complementary products that expedite the creation, editing, and real-time iteration of interactive 3D content. This accelerates the development process, enabling rapid deployment of digital twins.

Unity3D also shines in the domain of dynamic visualisation, supporting an extensive range of devices and platforms. With compatibility for over 20 platforms, including HoloLens, Quest, Windows, Mac, iOS, Android, and more, Unity3D emerges as a versatile choice for digital twin applications. It's not just versatility; Unity is a leading platform for crafting content for AR and VR applications, underpinning a substantial portion of head-worn AR experiences (Unity, n.d.)

To streamline digital twin development, Unity3D provides advanced simulation services. These services encompass sensor and robotics emulation, performance-optimised simulation testing, and training, among others. Collectively, these features expedite decision-making processes. Unity3D's hallmark features, including versatility, real-time capabilities, and extensive support for diverse devices and platforms, establish it as an indispensable platform for the visualisation and deployment of digital twins (Unity, n.d.).

The decision to adopt Unity as the foundational platform for the digital twin application is grounded in a solid foundation of reasons. Spatial rendering, especially for spatial-oriented data, presents a complex challenge that has long been the focus of the game industry. This challenge has led to the development of specialised software, often called game engines, which offer comprehensive toolsets and reusable components finely tuned for 3D rendering. In this landscape of options, Unity emerged as the optimal choice for the project, bolstered by familiarity with the platform, rooted in a background as a game development student (Leskovsky et al., 2020).

Unity earns favour for several compelling reasons. It provides extensive support for all essential aspects of the planned development, both directly and indirectly. Unity's user-friendliness ensures ease of learning, and its cost-effective pricing conditions are noteworthy. Moreover, Unity boasts comprehensive documentation and is distinguished for its rapid growth, continuously introducing new functionalities.

By choosing Unity, the potential of this versatile 3D engine is unlocked. It empowers the crafting of three-dimensional objects within a virtual space, offering dynamic manipulation, movement, and rotation. It also allows for the seamless integration of data from IoT devices. In the case of the crane, equipped with a multitude of IoT sensors, Unity's prowess in gathering and processing data from these sensors is invaluable. In the context of digital twin development, reliance on Figure 2, a schematic diagram illustrating the integration of Digital Twins within Unity3D serves as a valuable reference for the project (Gao et al., 2023). These capabilities lay the foundation for the immersive environment that the digital twin requires.

A diagram of a cloud server

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*Figure 2 – A schematic diagram of using Digital Twins in Unity3D (Gao et al., 2023).*

The camera, a pivotal component in 3D applications, plays a central role in shaping the user's viewpoint and impacting application control and display. Our application offers a spectrum of camera view modes, catering to diverse user needs, from PC desktop viewing to immersive VR experiences with headsets like Oculus. Unity's cross-platform compatibility is a standout advantage, allowing us to develop a unified application seamlessly running across platforms, spanning PCs, mobile phones, and the web. Unity further equips us with robust VR and AR tools that intuitively adapt the camera and interface to accommodate users and their equipment, whether involving a joystick, headsets, or other devices (Gao et al., 2023).

This combined section emphasises Unity3D's pivotal role in digital twin development and offers a comprehensive perspective on the reasons for choosing Unity as the foundational platform for our digital twin application.

## Case Study



### Importance of Case Studies

In the realm of technological advancements and systems improvement, case studies play a pivotal role in showcasing the significance of innovation. The case of DIAMND (Diagnostics and Monitoring), a Crane Management System, serves as a compelling example of how such studies shed light on the transformation of existing systems. It highlights the importance of critically examining and addressing the challenges posed by legacy technologies, especially when it comes to aesthetics and functionality. The importance of this case study lies in its potential to inspire others to explore new, more efficient solutions and improve the user experience, as well as to create visually appealing interfaces for data management systems.

### DIAMND: An Overview

In this case study, the goal is to address the limitations of the DIAMND system and propose a more effective solution. According to Dr David McMahon from Liebherr (2023), the existing DIAMND system used for crane management faces various challenges, particularly in terms of appearance and functionality.

Throughout this project, active engagement with members of the sales and engineering teams at Liebherr has been crucial in gathering insights and requirements for the improved system. These inputs have played a significant role in shaping the approach. This case study highlights the potential of modern technology and data-driven solutions in not only overcoming the limitations of legacy systems like DIAMND but also in improving the overall user experience and aesthetics of crane management operations.



#### Addressing The Challenges

In this section, the existing DIAMND system is examined, highlighting the imperative need for its transformation. DIAMND serves as the primary approach to crane management, but it presents a series of challenges, particularly in terms of aesthetics and functionality. These challenges stem from its reliance on data acquisition from various sources, including direct connections to a crane's PLC through SignalR and OPC-UA, hourly trace files containing approximately 35,000 signals, and feedback arrays within the PLCs, which are used to populate job and load statistics tables in SQL.

One of the significant challenges is the complexity of data management. The DIAMND system grapples with the intricacies of data acquisition, storage, and presentation. Diverse data sources not only make data management convoluted but also introduce noise and irrelevant information into the system. This noise can obscure critical data, contributing to inefficiencies and suboptimal data aesthetics.

Another issue is the outdated user interface. As highlighted in Figure 3 and Figure 4 below, the user interface of the DIAMND system is visually unappealing and does not align with modern design principles. This not only impacts the user experience but also underscores the pressing need for a modern and visually pleasing solution. It's worth noting that the current interface appears thrown together, lacking proper labels, and missing the company's distinctive touch, including its logo.

*A screenshot of a computer

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*Figure 3 – A view of the main spreader information displayed in DIAMND (Liebherr, 2023).*

A screenshot of a computer

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*Figure 4 – A view of some spreader information displayed in DIAMND (Liebherr, 2023).*

#### Proposed Solutions

To address these formidable challenges, a comprehensive transformation of the DIAMND system is proposed to streamline data management and enhance the user experience. Firstly, the utilisation of an API (Application Programming Interface) is recommended to seamlessly query data from an OPC-UA Server, connected to PLC, for certain variables and send it to an Azure database. This streamlined approach simplifies data acquisition, ensuring that relevant information is obtained swiftly and accurately. Secondly, data will be securely stored in an Azure database, offering enhanced data management capabilities. The Azure platform provides scalability, reliability, and accessibility, facilitating efficient data storage and retrieval. Lastly, to improve data aesthetics and user-friendliness, the implementation of Power BI for data visualisation is proposed. This powerful tool enables the creation of clear and visually appealing data presentations, making it easier for users to derive insights from the information.

The proposed solutions promise to mitigate the challenges faced by the existing DIAMND system, offering a path toward more efficient, user-friendly, and visually appealing crane management, in alignment with contemporary standards and user expectations.

### Lessons from Previous Implementations

Drawing on lessons from previous implementations, the DIAMND case study provides valuable insights for future projects. By examining the challenges and successes of this transformation, lessons can be extracted that extend beyond crane management. The key takeaway is the importance of aligning technology with user expectations and needs. Learning from this case study can guide future implementations, ensuring they are more efficient, user-friendly, and aesthetically pleasing.

## Internet of Things (IoT)



### Fundamentals of IoT

The IoT represents a transformative concept introduced by Kelvin Ashton in 1999, facilitating the connection of physical objects through the Internet to establish a platform for various activities (Gamil et al., 2020). The IoT framework encompasses a network of physical objects embedded with sensors, software, and other technologies, enabling data exchange with other devices and systems over the Internet. The current IoT landscape boasts around 14.76 billion connected devices (Howarth, 2023), with Oracle (n.d.) projecting a surge to over 22 billion by 2025.

The IoT framework is theoretically organised into four distinct layers, seen in Figure 5, that collectively contribute to its functionality. The application layer serves as a hub for various applications and services, ranging from smart cities and homes to transportation, utilities, and healthcare. In this layer, IoT manifests its diverse applications, becoming an integral part of modern living. The perception layer introduces sensory technologies like temperature, vibration, pressure sensors, and RFID (Radio Frequency Identification) sensors, allowing devices to gain awareness of their surroundings. This layer is pivotal in facilitating the acquisition of real-world data by IoT devices. The network layer is the communication backbone, encompassing both software and physical components that enable data transmission between devices and receivers. Its role is fundamental in ensuring seamless connectivity and interaction within the IoT ecosystem. Finally, the physical layer constitutes the basic hardware elements, including physical components, smart appliances, and power supplies, forming the infrastructure that supports the networking of smart objects. Each layer plays a crucial role in shaping the intricate fabric of the IoT (Kumar et al., 2016).

A diagram of a network layer

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*Figure 5 – The four layers that make up the IoT (Kumar et al., 2016).*

### IoT and Industry 4.0

Industry 4.0 represents an important paradigm shift in the manufacturing sector and involves the integration of information and communication technologies into industrial processes. Formed in Germany, Industry 4.0 represents the fourth industrial revolution, after the era of mechanical energy (Industry 1.0), mass production (Industry 2.0), and the digital revolution (Industry 3.0). At its core, Industry 4.0 relies on the fusion of CPS (Cyber-Physical Systems), CM (Cloud Manufacturing), and the IoT. CPSs comprise machines, storage systems, and production facilities capable of autonomously exchanging information, triggering actions, and monitoring one another. These systems combine virtual and physical elements of production by integrating analogue and digital devices. The Internet of Things is the key technology of Industry 4.0, providing the platform to connect CPSs through a network of sensors, actuators, and devices. CM, a concept born from Industry 4.0, harnesses the capabilities of cloud computing in external data centres to optimise production processes. This harmonious integration of technologies underpins the Industry 4.0 revolution, fostering a new era of smart manufacturing characterised by efficiency, connectivity, and data-driven decision-making (Ben-Daya et al., 2017).

### IoT Integration and Digital Twinning Integration

After elucidating the fundamentals of IoT and its crucial role in Industry 4.0, attention now turns to the transformative amalgamation with Digital Twinning, unveiling its practical application in refining construction processes. The convergence of IoT with Digital Twinning heralds a groundbreaking advancement in technological capabilities. The seamless connectivity facilitated by IoT aligns seamlessly with Digital Twinning's virtual replication of physical entities. Within this integrated framework, IoT sensors and devices continually gather real-time data from the physical environment, ensuring a constant update of corresponding digital twins. This dynamic interconnection significantly enhances comprehension of the physical system's behaviour, performance, and potential issues (Gamil et al., 2020).

In the context of the overarching Digital Twinning in Cranes project, the synergy between IoT and Digital Twinning goes beyond mere connectivity. It enables the creation of virtual replicas of cranes that are continuously updated in real-time. This functionality not only facilitates advanced monitoring but also empowers predictive maintenance capabilities. This harmonious integration becomes a catalyst for optimising crane operations, resulting in reduced downtime and an overall enhancement of efficiency in construction processes (Gamil et al., 2020).

Moreover, the significance of real-time monitoring is underscored by its application in construction project management. Observations derived from websites and sensor-based information prove pivotal in advancing critical stages of construction projects (BIM Engineering, 2018). These insights, by minimising delays and fostering efficient operational strategies, play an invaluable role. IoT solutions complement this by providing real-time alerts to supervisors concerning resource shortages or operational issues, highlighting real-time monitoring as a top-tier application of IoT. This proactive approach effectively mitigates downtime caused by stockouts or employee performance issues. The amalgamation of IoT-driven real-time observations and Digital Twinning's virtual replication establishes a comprehensive framework for elevating construction project management and operational efficiency.

## Big Data and Visualisation



### An Overview

In the contemporary business landscape, success is intricately tied to the effective utilisation of data. The evolution of technology and the internet has led to an unprecedented proliferation of information, making data a cornerstone of every successful enterprise.

Big Data refers to extensive datasets characterised by complex structures that present challenges in storage, analysis, and visualisation. With the continuous growth in data generation from various sources such as online transactions, social interactions, and IoT devices, businesses and organisations are compelled to explore innovative approaches for managing and extracting value from these vast datasets (Allaymoun et al., 2022).

Big data encompasses vast and exponentially growing quantities of information. Traditional data analytics tools face challenges in analysing such massive datasets, with examples including the daily generation of over 1 TB of data by the New York Stock Exchange and 400 TB+ daily data by social media platforms like Facebook (Rana et al., 2023).

### Classifying Big Data

Delving into the taxonomy of big data, Rana et al. (2023) provide valuable insights into its various types, namely structured, unstructured, and semi-structured data. Each category brings its own set of characteristics, highlighting the multifaceted nature of data in contemporary analytics.

Structured data is represented in a well-defined manner, often in the form of rows and columns. It is easily amenable to data models, facilitating relationships, updates, deletions, and modifications. The security features of structured big data are also relatively straightforward.

In contrast, unstructured data lacks a definite structure and cannot be easily fit into data models. This type of data is often portable and scalable, presenting challenges in storage due to the absence of a proper schema.

Semi-structured data possesses some structure but does not conform to a rigid data model. It includes metadata for grouping and describing data, offering flexibility and portability. While queries on structured big data are more efficient, semi-structured data accommodates diverse properties and sizes within the same group.

A diagram of a big data

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*Figure 6 – Big Data Types (Rana et al., 2023).*

### Benefits and Challenges of Big Data Analysis

The analysis of large datasets offers substantial benefits, including the development of efficient techniques for predicting future observations and gaining insights into the relationships between different variables. Big data analytics, with its focus on exploring heterogeneity and commonality across subpopulations, provides a unique opportunity to uncover hidden structures and extract essential common traits.

The landscape of big data analytics is evolving rapidly, driven by technological innovations such as big data and cloud computing. Cloud-based delivery models, exemplified by platforms like Amazon’s Big Data Analytics and SAP Big Data Analytics, offer scalable and accessible solutions for organisations seeking to harness the power of big data (Allaymoun et al., 2022).

Despite the advancements, challenges persist in efficiently pricing and distributing data in big data services. To address this, an auction-based big data market model is proposed, incorporating considerations of data size and analytics performance. The integration of machine learning algorithms and Bayesian profit maximisation auctions aims to provide a rational and computationally efficient mechanism for optimising service pricing and data distribution (Allaymoun et al., 2022).

### Data Visualisation in the Era of Big Data

Data visualisation, the graphical representation of information, has long been a valuable tool for conveying complex concepts quickly and effectively. Traditionally, data visualisation has been instrumental in detecting patterns in data; however, with the exponential growth of data, traditional approaches are becoming obsolete (Allaymoun et al., 2022). Now, more than ever, the importance of data visualisation is huge: it helps people see, interact with, and better understand data. Whether simple or complex, the right visualisation can bring everyone on the same page, regardless of their level of expertise.

In the realm of IoT, Data visualisation emerges as a state-of-the-art technology. The continuous stream of information from IoT devices gains exponential value through meaningful insights derived from visualisation techniques. Visualisation serves as a bridge between raw data streams and actionable insights, enhancing users' understanding of data patterns and trends (Allaymoun et al., 2022).

The intersection of Big Data and the IoT is a critical juncture in the technological landscape. IoT focused on assigning IP addresses to every object and enabling their interconnectedness, generates massive volumes of data. Big Data analytics becomes indispensable in extracting meaningful conclusions from the raw data churned out by trillions of interconnected devices (Allaymoun et al., 2022).

The characteristics of IoT data align with the defining features of Big Data, encompassing volume, variety, velocity, veracity, and value. The sheer volume of data generated by IoT devices, its diverse forms, real-time streaming, reliability, and the practical value it provides contribute to categorising IoT data as Big Data.

A diagram of a big data flow

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*Figure 7 – Big Data and IoT relationship (Mukherjee et al., 2022).*

The symbiotic relationship between Big Data and IoT is evident in their mutual benefits. While Big Data enables real-time analysis of IoT-generated data, the growth in IoT technologies prompts a demand for greater Big Data capacities. This reciprocal interaction drives technological advancements in both fields.

### Data Visualisation in the IoT Landscape

Data analytics in IoT involves analysing datasets to extract fundamental conclusions and valuable insights. Effective data analytics is crucial for advancing IoT applications and ventures, providing the necessary tools for making informed decisions based on the analysed data.

The transformative potential of insights derived from IoT data hinges on robust reporting and visualisation tools. Key factors influencing effective data visualisation in IoT include identifying pertinent information, selecting an appropriate reporting style, simplifying reports, considering enterprise data integrations, and establishing best practices for streamlined reporting (Il-Agure & Dempere, 2022).

IoT visualisation systems incorporate custom dashboard interfaces to aid users in analysing raw metrics. These dashboards provide real-time updates, interactive elements, and clarity, enhancing operators' confidence in AI models. Various visualisation models, including Tableau, Thingsboard, IBM Watson, Grafana, and Kibana Platform, offer diverse approaches to presenting and simulating IoT metrics.

### Data Visualisation and Unity

The integration of Unity, a robust game development engine, with Adobe Photoshop, introduces a dynamic synergy that transcends traditional boundaries in data visualisation, especially considering the limited availability of dedicated visualisation tools compatible with Unity. While Unity provides a powerful platform for creating immersive and interactive environments, the existing tools for intricate data visualisation within Unity are scarce. This scarcity highlights the significance of incorporating external software, such as Adobe Photoshop, to meet the advanced visualisation needs. By combining Unity's game development prowess with Photoshop's sophisticated visualisation capabilities, creators can unlock a new dimension in visual storytelling, addressing the challenges posed by the absence of dedicated data visualisation tools tailored for Unity. The result is a harmonious blend of Unity's interactive potential and Photoshop's graphic finesse, offering a unique solution to the limitations of conventional data visualisation tools within the Unity framework.

In addition to leveraging Adobe Photoshop for advanced visualisations in Unity, another viable option is the integration of Power BI, a robust business analytics tool, seamlessly embedded within the Unity environment. This integration not only expands the visualisation capabilities within Unity but also provides a user-friendly interface for dynamic data exploration. By embedding Power BI into Unity, developers and designers can harness its rich features for data analysis, reporting, and interactive dashboards, seamlessly merging the functionalities of both platforms. The combination of Unity, Adobe Photoshop, and Power BI offers a comprehensive solution to the challenges posed by the lack of dedicated visualisation tools, allowing creators to craft visually engaging and data-driven experiences within a unified development environment.

In the context of handling substantial datasets, opting for a business intelligence (BI) tool like Microsoft Power BI, as advocated by Rana et al. (2023), proves advantageous compared to conventional tools like Excel. One notable advantage lies in the superior processing speed of Power BI, outpacing Excel's capabilities when dealing with extensive data volumes. The visualisations crafted within Power BI are not only faster but also more aesthetically appealing, enhancing the overall user experience. The utility of Power Queries further facilitates the manipulation of vast datasets with ease, providing a streamlined approach to data management. In contrast, Excel encounters limitations, capping at 1.4 million rows and 16.38 thousand columns, rendering it inadequate for handling big data scenarios. Relying on Power BI, as recommended by Rana et al. (2023), addresses these shortcomings, offering a robust solution for efficient data processing, visually compelling representations, and seamless data manipulation in the realm of extensive datasets.

### Data Acquisition in Industry 4.0

Data acquisition in Industry 4.0 big data analytics systems involves collecting data from field devices for storage, visualisation, and analytics. Common data communication protocols such as OPC-UA and Modbus enable real-time or batch-oriented data collection. IoT gateways play a crucial role in data gathering, providing services like protocol translation, encryption, data processing, and wireless networking (Kahveci et al., 2022).

The accessibility and affordability of sensors allow industrial devices to generate massive amounts of data. IoT-enabled cloud platforms, exemplified by solutions like GE’s Predix, ABB’s Ability, and Microsoft Azure, offer capabilities for analysing raw production data. However, these platforms introduce dependencies on external connectivity, proprietary technologies, and custom implementation (Kahveci et al., 2022).

## Communication Protocols



### An Overview.

Communication protocols play a crucial role in enabling the seamless exchange of data and information across networks. These protocols are sets of formal rules that define how data should be transmitted or exchanged, especially in the context of real-time monitoring and the IoT. Various standardised communication protocols facilitate the availability of data through different channels, such as web servers using HTTP (Hypertext Transfer Protocol), file servers through FTP (File Transfer Protocol), or well-documented APIs. In addition, other examples include TCP/IP (Transmission Control Protocol/Internet Protocol), UDP (User Datagram Protocol), POP3 (Post Office Protocol), CoAP (Constrained Application Protocol), XMPP (Extensible Messaging and Presence Protocol), AMQP (Advanced Message Queuing Protocol), IMAP (Internet Message Access Protocol), and SMTP (Simple Mail Transfer Protocol) (Rouse, 2023).

A diagram of a cloud computing system

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*Figure 8 – Types of Communication Protocols (Bayılmış et al., 2022).*

One notable protocol that has evolved beyond its original purpose is HTTP, which, through APIs, allows computer applications to efficiently share and access machine-readable data across the internet. APIs, or Application Programming Interfaces, act as messengers facilitating the interaction between software applications, systems, or platforms for data exchange (Airfocus, n.d.). MQTT also stands out as one of the most used, with HTTP leading the way in terms of widespread adoption. HTTP, originally designed for transmitting web pages, has evolved into a versatile protocol, particularly favoured for its simplicity, flexibility, and ease of integration. Its dominance is evident in its ranking as the most used protocol, as reflected in the 2020 data where it slightly outpaces MQTT. This preference for HTTP underscores its ubiquitous role in facilitating data transfer in web-centric applications and real-time projects. Meanwhile, MQTT, known for its efficiency in resource-constrained environments, continues to be a formidable choice, particularly in scenarios where low-cost reliability and asynchronous communication are critical. The dynamic between HTTP and MQTT exemplifies the nuanced decision-making involved in selecting communication protocols and aligning with project requirements and priorities. (Bayılmış et al., 2022).

A graph of different colored lines

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*Figure 9 – Most used IoT Communication Protocols (Bayılmış et al., 2022).*

In the realm of real-time monitoring and IoT, communication protocols are vital for capturing and transmitting data efficiently. For instance, in fleet management, real-time data collection through vehicle fleet management software utilises communication protocols to monitor factors such as reckless driving or driver impairment, optimising fleet utilisation (Barney, 2023). In industrial scenarios, communication protocols like Modbus TCP/IP are employed to connect digital dashboards with Human-Machine Interfaces (HMI) and databases, ensuring real-time and reliable data exchange (Khan et al., 2020). Additionally, MQTT is a messaging transport protocol with a publish-subscribe architecture widely used in IoT applications, providing a reliable and efficient means of communication between devices (Bayılmış et al., 2022). The open OPC UA protocol is utilised to break communication barriers between virtual and real environments, enabling seamless data interaction in monitoring systems (Zhou et al., 2022).

### MQTT

MQTT stands out as a robust communication protocol, particularly well-suited for resource-constrained environments and scenarios where low-cost, open-source reliability and simplicity are paramount (Bayılmış et al., 2022). Developed with a publish-subscribe architecture, MQTT facilitates efficient messaging between clients and brokers. In this model, clients can take on the roles of either publishers or subscribers, and communication is achieved through topics assigned by the broker. MQTT's ability to handle different levels of QoS (Quality of Service) and its support for TCP/IP and TLS/SSL (Transport Layer Security/Secure Sockets Layer) make it a versatile choice for IoT applications (Bayılmış et al., 2022). With a focus on minimising data size, MQTT is designed to provide real-time communication for devices with limited resources, making it an excellent option for scenarios demanding lightweight and reliable messaging. (Bayılmış et al., 2022).

### REST

On the other hand, REST operates on an architectural style for networked systems, primarily using the HTTP protocol. Widely adopted for its simplicity, flexibility, and ease of integration, REST is a preferred choice for web-based applications (Barney, 2023). RESTful services adhere to a stateless client-server model, with data transfer accomplished through standard HTTP methods such as GET, POST, PUT, and DELETE. The REST architecture treats each component as a resource, accessible through a Uniform Resource Identifier (URI). This simplicity, coupled with the ability to use various data formats like JSON or XML, makes REST well-suited for real-time projects where a straightforward communication model and web-centric interactions are crucial (Barney, 2023). The stateless nature of REST simplifies implementation and ensures seamless integration, making it an attractive option for applications emphasising ease of use and standardised communication.

### APIs

APIs serve as essential tools in software development, facilitating interaction between different software applications, systems, or platforms by defining a set of rules and protocols for communication. An API acts as a messenger that enables the exchange of data between diverse software components. It allows developers to access the functionality of an application or service without delving into its internal workings. APIs play a pivotal role in enhancing interoperability, scalability, and efficiency in software development. They enable the seamless integration of various services and functionalities, promoting a modular and collaborative approach to building software systems. APIs can be used in a myriad of scenarios, from enabling social media logins and processing payment transactions to implementing price comparison features for vacations. Their versatility makes them a fundamental component of modern software architecture. APIs should be employed when there is a need for different software components to communicate and share data in a standardised and efficient manner. They provide a means for developers to harness the capabilities of existing services, fostering innovation, and streamlining the development process (Barney, 2023).

### Real-Time Monitoring

Real-time monitoring, as defined by Barney (2023), is the continuous delivery of updated data pertaining to systems, processes, or events with minimal latency between data collection and analysis. This approach involves the meticulous collection and storage of performance metrics as data traverses a network, utilising polling and streaming mechanisms from infrastructure devices. The significance of real-time monitoring lies in its ability to bridge the critical gap between the time a problem occurs and the time it is addressed. This is particularly crucial as delays in reporting and subsequent action can result in substantial financial costs. Real-time monitoring addresses this challenge by providing instantaneous data, alerts, and notifications. By offering a constant stream of information, organisations can promptly identify and respond to issues, ensuring that proactive measures are taken swiftly. This not only aids in preventing potential disruptions but also enhances overall system efficiency and reliability, making real-time monitoring an indispensable component in contemporary operational frameworks.

## Cloud Computing

Cloud computing, a transformative paradigm, provides users with internet-based access to diverse computing services, eliminating the need for on-site infrastructure. This model, featuring on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service, allows flexible resource management and cost-effectiveness. With three service models—Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS)—cloud computing supports various applications, from basic storage to advanced data analytics. In the context of the IoT, cloud technologies are crucial for managing the exponential growth of data. Cloud service models, including private, public, and hybrid options, offer versatile solutions for IoT integration. While financial considerations impact deployment choices, cloud computing remains a vital enabler for scalable and efficient IoT operations, aligning with industry trends (Khan et al., 2020).



# Methodology



## Research Undertaken

This project's research primarily focuses on digital twins, data visualisation, and real-time monitoring. Digital twins are explored for their potential in enhancing ergonomic assessments by creating virtual replicas of physical processes. The study investigates real-time monitoring methodologies, including sensors and IoT, to establish a robust monitoring infrastructure. Additionally, the research emphasises the importance of data visualisation techniques, such as dashboards and 3D visualisations, to present complex spatial data in a comprehensible manner.

## Research Question

The central focus of this project is to investigate the impact of implementing Digital Twin technology alongside a fleet monitoring dashboard. The primary research question guiding this study is:

"Does the implementation of Digital Twin technology, coupled with a fleet monitoring dashboard, contribute to enhancing the visual clarity and overall user experience in crane system monitoring?"

## Proposed Implementation

The project's primary goal is to develop a comprehensive solution for crane system monitoring by integrating a Unity-based digital twin and a Photoshop-designed dashboard. The Unity digital twin will be instrumental in replicating and visualising historical data received from crane operations, providing a dynamic representation of the crane systems. Concurrently, a user-friendly dashboard will be created in Photoshop to seamlessly interface with the Unity digital twin, offering an accessible platform for users to monitor and interpret key spatial and operational data. The Unity digital twin will leverage real-life historical crane data to accurately mimic and simulate crane operations within a virtual environment.

## Functional Design

### Risk Analysis

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Description** | **Likelihood** | **Impact** | **Mitigation Activity** | **Plan of Action** |
| Data cannot be acquired | Low | High | Look for an alternative dataset on Kaggle | Be in frequent contact with company and ensure data delivery |
| Not enough data is available | Low | High | Reach out promptly to explore and acquire additional data. | Frequent communication with the company to obtain requirements in a timely manner |
| Data requires pre-processing | Medium | Low | Use the KDD process to pre-process the data | Use the KDD process to pre-process the data |
| Uncertainty in Physics and Forces Data | High | Medium | Use the best available data to create the most accurate digital twin. | Implement a continuous improvement process to update the model when updates are available |

*Table 1 – Risk Analysis Table.*

### Functional Specifications

The MoSCoW method is a prioritisation technique used in project management to categorise requirements into four priority groups: Must-haves, Should-haves, Could-haves, and Won't-haves. Here's a bit more detail on each category (Brush, 2023).

|  |  |  |  |
| --- | --- | --- | --- |
| **Must Have** | **Should Have** | **Could Have** | **Won’t have** |
| Digital Twin Integration | Real Time Data Integration | AR/VR Integration | Mobile Application |
| Monitoring Dashboard | Data Storage and Retrieval | Interactive Dashboard | Predictive Analysis |
| Using Data set from Real World Cranes |  | Customisable Dashboard | Alerting System |

*Table 2 – MoSCoW Method.*

## Data Collection and Analysis

Data is collected via the Crane’s PLC in the form of .trc files. These files encompass an extensive dataset, comprising over 30,000 variables that encapsulate the nuanced details of the STS crane's operation at specific timestamps. Employing Liebherr's trace tool program proves instrumental in navigating this wealth of variables, facilitating the extraction of those most pertinent to the project's objectives. This tool streamlines the process of organising and extracting the selected variables, which are subsequently exported into a CSV file. The initial dataset used for prototype one was provided by our team; however, for future iterations, the plan is to autonomously handle the data collection process. Additionally, before deployment, thorough cleaning and validation processes will be implemented to ensure the integrity and reliability of the data before its incorporation into the project.

## Prototype

In the initial phase of developing Prototype 1 for the digital twin in Unity, the focus was on implementing basic functionality, starting with the movement of the trolley. The foundation was laid by coding an incremental loop that enabled manual control of the trolley's position within the virtual environment. Once this fundamental movement was successfully established, the next step involved introducing a more dynamic and realistic element. Values representing the trolley's position were then read in from a CSV file, a process integral to mirroring real-life crane movements. This approach allowed for a more nuanced and data-driven simulation, aligning the digital twin's behaviour closely with the operational data collected from the physical crane.

A computer screen shot of a bridge

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*Figure 10 – Unity Scene for Prototype 1.*

# Implementation



## Sprint One (Jan 18th – Feb 1st)

During the initial sprint, tasks encompassed data manipulation using a trace tool, setting up a Unity project, establishing a scene for the digital twin, integrating crane data into a 3D environment, and designing a user interface in Photoshop.

|  |  |  |
| --- | --- | --- |
| Task | Description | Status |
| 1 | Manipulate data via Trace Tool | Complete |
| 2 | Set up a project in Unity | Complete |
| 3 | Set up a scene for the Digital Twin | Complete |
| 4 | Integrate data from task one with Digital Twin | Complete |
| 5 | Design the first draft of the UI in Photoshop | Complete |

*Table 3 – Sprint one tasks.*

### Task 1

In the preliminary project phase, the utilisation of Liebherr’s trace tool facilitated a comprehensive exploration of raw data. The tool's functionality enabled effective manipulation and analysis, leading to the extraction of valuable insights. The result was the creation of a meticulously structured .csv file, containing pertinent information for subsequent integration into the Unity environment.

A screenshot of a computer

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*Figure 11 – Liebherr Trace Tool.*

### Task 2

The initiation of the development process involved the creation of a new Unity project. This encompassed the configuration of project settings, the establishment of a clear project structure, and alignment with the digital twin initiative's requirements. The setup in Unity laid a sturdy foundation for ensuing tasks, streamlining the overall development workflow.

### Task 3

A basic scene was set up with the crane model, as illustrated in Figure 10 above. This involved the incorporation of the crane model into the Unity environment, establishing a preliminary spatial layout for the digital twin. This foundational step set the stage for subsequent tasks related to crane data integration.

### Task 4

Leveraging the prepared .csv file, the successful integration of manipulated data into the Unity 3D environment was achieved. This encompassed mapping crane data to corresponding elements within the scene, generating a dynamic representation of real-world crane operations. The integration process facilitated seamless data visualisation in a 3D space. Two key classes, namely ReadData and CraneMovement, played crucial roles in achieving this goal.

The ReadData class handles asynchronous reading of crane data from a CSV file. It utilises a coroutine to continuously read and update trolley and hoist positions based on the CSV data. The class ensures proper error handling and provides flexibility with a configurable delay between data reads.

The CraneMovement class orchestrates the real-time visualisation of crane components in the Unity scene. It relies on the positions obtained from the ReadData class to dynamically update the positions of the trolley and hoist game objects. The continuous Update method ensures synchronised movement in the Unity environment, offering a visually representative digital twin of the crane operations.

### Task 5

In the pursuit of enhancing user interaction and data presentation, Photoshop was utilised to craft an intuitive and visually appealing user interface (UI). The UI design prioritised clarity and conciseness in displaying crane data, ensuring users could readily interpret and interact with information within the digital twin environment. This step aimed to enhance the overall user experience and facilitate efficient data analysis.

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*Figure 12 – First draft of UI*

### Results

The sprint concludes with the successful creation of a basic digital twin prototype, emulating historical crane movements. Additionally, a preliminary UI draft has been developed, setting the stage for further integration and refinement in subsequent phases.

## Sprint Two (Feb 1st – Feb 15th)

Sprint two focused on expanding the Unity project by integrating additional important data such as wind speed and weight. A redesigned user interface for a spreader view was implemented and seamlessly integrated into the Unity project. A useful feature introduced was a dynamic switch for users to effortlessly toggle between different views, enhancing flexibility and user engagement.

|  |  |  |
| --- | --- | --- |
| Task | Description | Status |
| 1 | Add more key data points into Unity project | Complete |
| 2 | Design new UI for Spreader analysis | Complete |
| 3 | Integrate UI and Unity project | Complete |
| 4 | Add feature to allow view spreader or full crane view | Complete |

*Table 4 – Sprint two tasks.*

### Task One

Task one in sprint two involved the retrieval of additional crucial data using the trace tool. This data, converted to CSV format, was seamlessly read by the Unity script, expanding the range of information integrated into the digital twin. By broadening the spectrum of data sources, the digital twin became enriched with additional parameters, such as wind speed and weight, elevating the overall accuracy and realism of the simulation.

### Task Two

The second task delved into the refinement of the user interface, specifically tailored for the spreader view. Building upon the initial UI draft, significant improvements were made to enhance clarity and usability. Notable enhancements included the incorporation of twist lock states and the transition from radial to linear gauges, offering users a more precise visual interpretation of data. Additionally, the introduction of labels in the top row provided explicit insights into the meaning of each reading, fostering a more intuitive understanding for users interacting with the spreader view.

A screenshot of a computer

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*Figure 13 – Update UI for Spreader Analysis.*

### Task Three

Task three seamlessly integrated the redesigned UI into the Unity project using the canvas element. Leveraging the expanded dataset from task one, the UI effectively displayed a comprehensive set of information, contributing to an enriched user experience within the digital twin environment.

A screenshot of a computer

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*Figure 14 – Unity & Spreader UI (Fig.13) integrated.*

### Task Four

The fourth task introduced a pivotal feature to enhance user interaction – a dynamic switch between different views. Through the implementation of a toggle and a snippet of C# code, users gained the capability to effortlessly navigate and toggle between various perspectives within the 3D environment. This not only added a layer of flexibility but also elevated user engagement, allowing for a more personalised and dynamic exploration of the digital twin's features and functionalities.

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*Figure 15 – Spreader Cam toggle on.*

### Results

The outcomes of sprint two yielded a digital twin that significantly advanced in both functionality and user experience. The expanded integration of trace tool data, including wind speed and weight, enriched the simulation's realism and accuracy. Users now benefit from a more comprehensive and nuanced understanding of the crane's behavior within the 3D environment. The refined spreader view UI, with its improved clarity and precise gauge representations, ensures a more user-friendly interaction, facilitating a more intuitive grasp of critical information. The successful integration of this enhanced UI into the Unity project further solidifies the cohesion of the digital twin, providing users with a seamlessly integrated platform for comprehensive data analysis. The introduction of the dynamic switch feature adds an extra layer of versatility, empowering users to effortlessly switch between different views and tailor their exploration based on specific needs, contributing to heightened engagement and usability. Overall, sprint two delivered a more sophisticated and user-centric digital twin, well-equipped to meet the evolving demands of the project.

## Sprint Three (Feb 15th – Feb 29th)

Sprint three marks the lift cycles being incorporated into the Unity project, providing a comprehensive representation of the crane's operational patterns. Concurrently, in task two, Azure Functions are developed to streamline and automate processes. In task three, the Unity project leverages these functions to store lift cycles in an Azure database, fostering efficient data management. The integration of Azure database sets the stage for task four, where lift cycle data is seamlessly implemented into Power BI for comprehensive visualisation and analysis. Sprint three not only expands the digital twin's functionality by incorporating lift cycles but also establishes a robust data pipeline, utilising Azure services to enhance storage, retrieval, and visualisation processes, thereby advancing the overall sophistication and utility of the digital twin.

|  |  |  |
| --- | --- | --- |
| Task | Description | Status |
| 1 | Add lift cycles & display them in Unity Project | Complete |
| 2 | Create Azure Functions | Complete |
| 3 | Use Function in Task 2 to store lift cycles in Azure database | Complete |
| 4 | Using Azure database implement the lift cycles into Power BI | Complete |

*Table 5 – Sprint three tasks.*

### Task One

In addressing the first task of sprint three, the focus was on integrating lift cycles into the Unity project, enhancing the digital twin's ability to accurately reflect the crane's operational patterns. The LineRendererManager.cs script stands at the core of this implementation. Through the utilisation of Unity's Line Renderer component, the script efficiently tracks the crane's movements over time, creating a visual representation of lift cycles. The script employs timers to control the frequency of point updates, ensuring a dynamic and detailed depiction of the crane's trajectory. Additionally, it distinguishes between various operational modes, dynamically adjusting the color of the automation line to provide clear visual cues. The creation of new line renderers for each lift cycle contributes to an organised and comprehensive visualisation of the crane's historical performance. This task sets the stage for subsequent tasks, establishing a foundation for efficient data management and external interactions in the ongoing development of the project.

### Task Two

The implementation of Azure Functions in sprint three represents a pivotal step towards achieving efficient data processing and storage within the digital twin project. The provided FunctionApp\_\_\_Database script encompasses two distinct functions: SendToArcValues and SendToLiftCycles, each responsible for handling specific data entries.

In the 'SendToArcValues' function, HTTP-triggered requests are processed, extracting essential data such as cycle ID, point, position coordinates, timestamp, and mode from the request body. Leveraging a secure SQL Server connection string, the function establishes a connection to the Azure SQL database and executes parameterized queries to insert the acquired data into the 'ArcValues' table. This seamless integration ensures the real-time storage of critical crane operational data.

Similarly, the 'SendToLiftCycles' function processes HTTP-triggered requests, extracting data related to lift cycle information, including cycle ID, start and end times, and total time. Mirroring the approach in the previous function, this data is securely inserted into the 'LiftCycles' table within the Azure SQL database. This function contributes to the holistic representation of crane performance, storing pertinent information on lift cycles for comprehensive analysis.

Both functions incorporate robust error-handling mechanisms, logging any encountered issues and returning appropriate HTTP status codes to facilitate effective troubleshooting and maintenance. This implementation of Azure Functions lays a foundation for seamless data flow between the Unity project and Azure SQL, crucial for creating a responsive, data-driven digital twin with the capability to handle, process, and store diverse operational data efficiently.

### Task Three

The collaboration between the Unity project and Azure Functions in tasks one and two streamlines the process of storing lift cycles in the Azure database. The 'LineRendererManager.cs' script in task one captures intricate lift cycle data within Unity, orchestrating the creation of line renderers and sending relevant information to external services. Task two introduces Azure Functions acting as the interface between Unity and the Azure SQL database. The functions process incoming HTTP requests, securely inserting data into the respective tables. In the Unity script, the 'GetPoints' method seamlessly invokes these functions, ensuring real-time storage of crane movements in the 'ArcValues' table and lift cycle details in the 'LiftCycles' table. This cohesive integration enhances the digital twin's functionality, creating a responsive system for processing and storing diverse operational data efficiently.

### Task Four

Task four marks a crucial step in enhancing data visualisation and analytics within the digital twin project. Leveraging the Azure database containing lift cycle information stored through Azure Functions, this task involves integrating the data seamlessly into Power BI for comprehensive analysis and visualization.

The process begins by establishing a connection between Power BI and the Azure database. Power BI provides a range of connectors and tools to facilitate this integration, allowing for the extraction of real-time data from the Azure SQL database. Once connected, the lift cycle data, including cycle ID, start and end times, and total time, can be imported into Power BI, enabling users to create dynamic and interactive reports and dashboards.

This integration not only provides users with a visually compelling representation of lift cycle patterns but also empowers them to derive valuable insights from the data. Power BI's analytical capabilities, combined with the real-time data flow from the Azure database, contribute to a more informed decision-making process and a deeper understanding of the crane's operational performance within the digital twin environment.

A screenshot of a computer

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*Figure 16 – Power BI with Lift Cycle data from Azure.*

### Results

The successful completion of the four tasks in sprint three marks a significant advancement in the capabilities of the digital twin project. The incorporation of lift cycles into the Unity project, managed by the 'LineRendererManager.cs' script, provides a detailed and dynamic visualization of the crane's operational patterns. This data is seamlessly transmitted to the Azure database through Azure Functions, establishing a robust data pipeline. Task four further enriches the project by seamlessly integrating lift cycle data from the Azure database into Power BI, enabling stakeholders to derive meaningful insights through interactive reports and dashboards. This collective effort enhances the digital twin's responsiveness, data processing, and visualisation capabilities. The real-time data flow, coupled with comprehensive analytics, positions the project for more informed decision-making, offering a powerful tool for monitoring, analysing, and optimizing crane performance within the digital twin environment. Overall, sprint three culminates in a sophisticated and interconnected system, laying the foundation for continued advancements in the project's functionality and utility.

## Sprint Four (Feb 29th – March 14th)

# Results



## Key Findings from the Implementation

## Data Analysis Results

## Successes and Challenges Encountered

# Discussion



## Interpretation of Results

## Comparing Findings with the Literature

## Insights Gained from the Study

# Conclusion



## Recap of Key Points

## Implications for Industry and Research

## Future Directions

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