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# Glossary

API – Application Programming Interface

AR – Augmented Reality

BIM – Building Information Modelling

CAD – Computer-Aided Design

CM – Cloud Manufacturing

CPS – Cyber-Physical Systems

DIAMND – Diagnostics and Monitoring

ERP – Enterprise Resource Planning

IoT – Internet of Things

OPC – Open Platform Communications

PLC – Programmable Logic Controller

PLM – Product Lifecycle Management

SQL – Structured Query Language

VR – Virtual Reality

# 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.

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, the concept of comparison becomes an indispensable analytical tool in the context of 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 not only monitor their fleet but also 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.

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.

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.

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.

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. The existing DIAMND system, used for crane management, presents several challenges, especially in terms of its appearance and functionality. It relies on data collection from various sources, including direct connections to a crane's PLCs through SignalR and Open Platform Communication (OPC), hourly trace files containing approximately 35,000 signals, and feedback arrays within the PLCs to populate job and load statistics tables in Structured Query Language (SQL).

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, 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

Description automatically generated

*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 Application Programming Interface (API) is recommended to seamlessly query data from an OPC 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 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 cyber-physical systems (CPS), cloud manufacturing (CM), 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 (Gamil et al., 2020). 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.

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.

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



### Big Data Collection and Analysis

### Data Visualisation Techniques

### Visualising Big Data

### Impact of Visualisation on Decision-Making

## Risk Analysis and Platform Issues



### Identifying Risks in Digital Twin Projects

### Evaluating Digital Twin Platforms

### Mitigation Strategies for Risks

### Case Studies of Platform-Related Failures

# Methodology



## Research Approach

## Data Collection Methods

## Data Analysis Techniques

# Implementation



## Real-World Application of Digital Twinning

## IoT Integration and Case Studies

## Big Data and Visualisation Implementations

# 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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