LEVERAGING DIGITAL TWIN FOR OPERATIONAL EXCELLENCE

by

Sujit Kumar Singh

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by

Sujit Kumar Singh

Supervised by

Dr. Jose Ramon Bronet

APPROVED BY

dr. Anna Provodnikova

Dissertation chair

RECEIVED/APPROVED BY:

Admissions Director

Dedication

To my beloved wife Ruchi for always being there as my Sri Sakhi, traversing with me to the horizon of life and beyond and my Sunshine, Angel & Shubhranshu.

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ABSTRACT

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Sujit Kumar Singh
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Dissertation Chair: <Chair's Name>
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This research project will look at how "Digital Twins" (DTs) can be utilized to improve the industrial and engineering industries' operational excellence. This research's primary goal is to close this knowledge gap and offer proof that DTs can enhance operations. The economic viability of DT adoption, the effects on KPIs, processes optimization, operational efficiency enhancement, product quality and consistency enhancement, and DT fusion technology with "Engineering, Procurement, and Construction" (EPC) principles to increase project efficacy are just a few of the topics this research will examine to meet its objectives. The research technique will adopt a descriptive and quantitative approach, incorporating data gathering using a questionnaire survey and subsequent statistical analysis using IBM's SPSS (Statistical Packages for Social Sciences). Economic benefits, effects on operational excellence, cost-cutting techniques, and methods for increasing operational efficiency are all things the study should illuminate. Research proves that DT technology positively and immensely affects productivity, resource utilization, and quality of output, and most of the respondents affirmed that they observed decreased downtime, minimized waste, and effective decision-making due to DT in their respective organizations. Furthermore, the integration of DT with EPC shows the effectiveness of DT in managing complex projects and enhancing project delivery. However, there was recognition of barriers to implementation, especially high initial costs. The study concludes that DT technology offers substantial long-term economic benefits and operational improvements, making it a valuable asset for organizations seeking competitive advantage. Theoretical implications include a clearer framework for evaluating DT impact on operational KPIs, while managerial implications highlight DT's role in resource optimization, project efficiency, and cost-effectiveness. Future research is recommended to explore industry-specific DT applications, sustainable impacts, and the integration of DT with artificial intelligence to maximize its potential.

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LIST OF ABBREVIATIONS

Abbreviations	Full Form
AECO	Architecture, Engineering, Construction, And Operations
AI	Artificial Intelligence
AR	Augmented Reality
BD	Big Data
BDA	Big Data Analysis
BPS	Bosch Production System
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CC	Cloud Computing
CFD	Computational Fluid Elements
CNNs	Convolutional Neural Networks
CPS	Cyber-Physical Systems
CPS	Cyber-Physical Systems
DC	Digital Shadow
DL	Deep Learning
DoD	Department Of Defence
DSCT	Digital Supply Chain Twin
DT	Digital Twin
DTP	Digital Twin Prototype
EPC	Engineering, Procurement, And Construction
EU	European Union's
FDT	Federated Digital Twin
HVAC	Heating, Ventilation, And Air Conditioning

IBPT	Industrial Business Process Twin
IESs	Integrated Energy Systems
IoT	Internet Of Things
IP	Internet Protocol
IT	Information Technology
KPIs	Key Performance Indicators
LSS	Lean Six Sigma
LSS	Lean Six Sigma
M2M	Machine-To-Machine
MDE	Model-Driven Engineering
MIMO	Multiple-Input Multiple-Output
ML	Machine Learning
MSTE	Mean State Transition Error
NLP	Natural Language Processing
O&M	Operations And Maintenance
ODEs	Ordinary Differential Equations
OEE	Overall Equipment Effectiveness
OLAP	Online Analytical Processing
OP	Operational Technology
OPC UA	Open Platform Communications United Architecture
PFT	Plant Factory Transplanter
PMS	Performance Measurement System
PMS	Performance Measurement System
ROI	Return On Investment
SDT	Spatial Digital Twin

SII-Lab	Stena Industry Innovation Lab
SMEs	Small And Medium-Sized Businesses
TAM	Technology Acceptance Model
TBL	Triple Bottom Line
TQM	Total Quality Management
TQM	Total Quality Management
VR	Virtual Reality
WBEM	Web-Based Enterprise Management
WBEM	Web-Based Enterprise Management

CHAPTER I:

INTRODUCTION

1.1 Overview

The term was first published by Michael Grieves at the University of Michigan in 2002, but due to the IoT, the concept of the digital twin has evolved a great deal. The fundamental component of a digital twin is a real-time digital replica of a system, process or service. Products, factories, and even whole company services can have digital twins thanks to this virtual representation, which expands its uses beyond simple systems and procedures. A digital twin's main purpose is to seamlessly integrate business, contextual, and sensor data from actual systems and processes into the virtual model. This integration facilitates thorough analysis, helps identify and prevent problems, and helps establish well-informed technological strategies. The digital twin enhances real-time decision-making by connecting the virtual and physical worlds (Azad M. Madni, 2019).

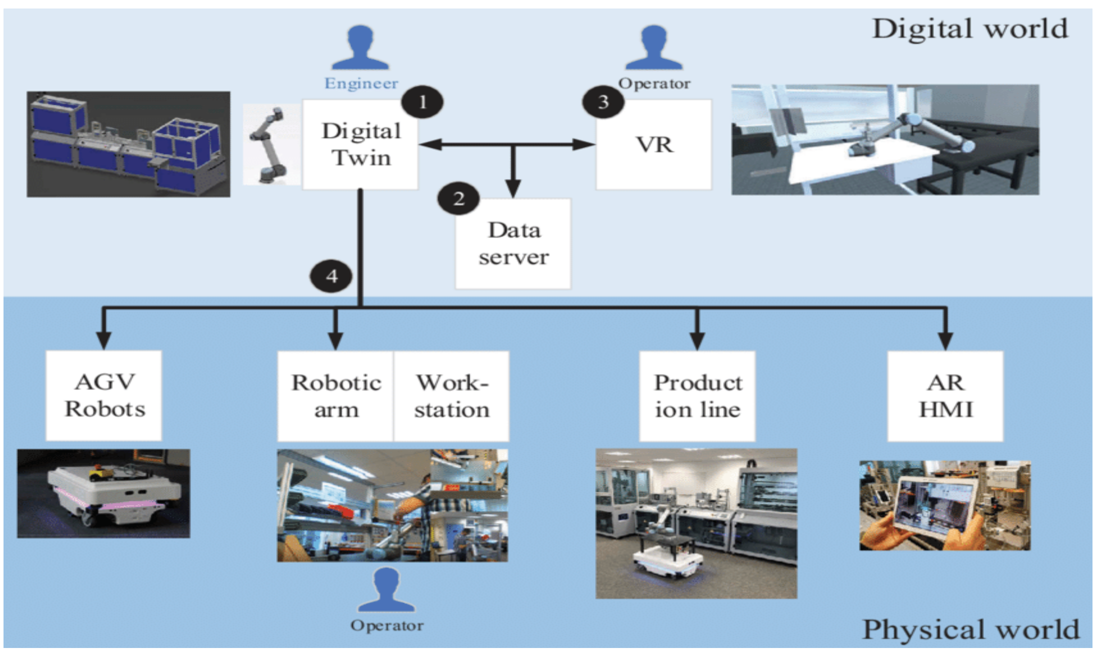

Figure 1: Overview of digital twins in real-time (Source: Havard 2019)

The digital twin allows real-time system and process monitoring between the virtual and physical worlds. This allows rapid data analysis to predict issues, schedule preventative maintenance, uncover new business opportunities, and plan future improvements. The digital twin represents a specific system or process, unlike normal virtual models, which represent a system, component, or family of components. This technique has huge potential to minimise system testing and verification costs and provide informative early warnings regarding system behaviour. In an increasingly interconnected world, the Department of Defence (DoD) Digital Engineering project uses digital twin technologies to connect systems and operations (Nader Mohamed, 2023).

Surprisingly, the last few years have witnessed an unprecedented digital shift in design and development of products. Owing to computer supported technologies like the computer aided design (CAD) or the computer aided engineering (CAE), engineers or designers can now develop new product designs with incredible ease. The majority of engineers can now easily construct 3D models that offer vital design help and verification thanks to advancements in CAD software, in particular. Not only is this a technological but also a collaborative move toward a comprehensive digital era in product design and development. Kunz, Smith and Tomiyama (2009) Various stakeholders, such as clients, producers, and designers, can now easily share concepts and expertise in a collaborative design setting. However, as the sophistication and applications of the digital models have increased to improve the design process and promote design cooperation, the question of how to best utilize them emerges. In order to improve the applicability of these models across numerous fields, the digital twin (DT) phenomenon has emerged. Engineers and designers can benefit greatly from the digital twin because of its clear potential to improve conventional product design and development procedures (Z. Liu et al., 2023).

1.2 Concept of Digital Twins

Mainly because of the usage of Internet of Things (IoT) technology, digital twin (DT) is one of the recent technologies that has seen light in the recent past. It acts as an electronic representation of how a physical system, product or service works to bring out certain results. It has the actual model together with a computer facilitated representation of the actual model. As they offer real-time, digital representations of the real world, the fundamental goal behind digital twins is to improve our capacity to understand, to learn, and make educated judgments regarding dynamic environmental changes (Ruzsa, 2020).

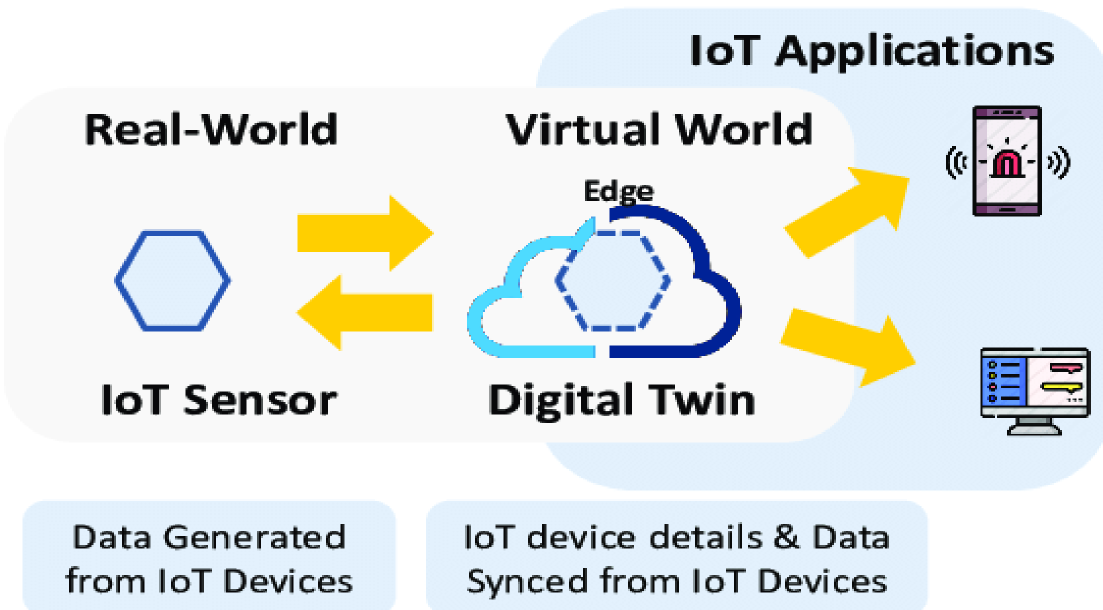

Figure 2: Data transmission in digital twin (Source: Shapna 2020)

Many sectors take advantage of digital twin technology, which provides a number of advantages for both manufacturers and customers. It is utilised by combining a number of modern technologies, including artificial intelligence (AI), big data, sensors, IoT, and simulation. The following summarises the operation of digital twins:

- **Sensors:** To gather information on a physical asset's performance, behaviour, and state in real time, sensors have been placed on it. A great deal of data, such as location, pressure, temperature, and more, can be recorded by these sensors.
- **Simulation:** A digital model or simulation of the real-world system or item is made using the sensor recordings. Every time something changes in the actual world, its digital representation is updated accordingly.
- **Internet of things (IoT):** The connection between the digital and physical assets happens through the Internet of Things (IoT). This link enables data to flow from one system to the other and vice versa between the physical twin and the real environment.
- **Big Data:** These technologies handle and analyse the vast amounts of data produced by sensors. Environmental factors, performance measurements from the present, and historical records are all included in this data.
- **Artificial intelligence:** It includes both machine learning and Artificial Intelligence: For data acquisition from sensors and records or past data, machine learning and AI algorithms are applied. The given analysis allows to identify trends, abnormities and possibly improvements.

The utility of digital twins is that they are useful across many domains of operations and decision making. Digital twins have a significant impact on the following important areas:

- **Performance Improvement:** As a result, digital twins contribute to the capability of designing approaches for performing active maintenance and performance enhancement of physical systems that can be monitored and analysed in real time. This results in improved performance and a lot of time is not wasted.

- **Predictive maintenance**: It uses digital twins to analyse real-time data and forecast when systems or equipment could fail. This reduces expenses and avoids unplanned breakdowns by helping arrange maintenance tasks at the right times.
- **Scenario Simulation:** As a consequence, digital twins have the capacity to model numerous situations and to evaluate the changes which are regarded in relation to the real world. This capacity helps companies to decide since it anticipates the potential outcomes of the undertakings that have been planned**.**
- **Quality Assurance:** Since adjustments may be made in real time to satisfy the stringent quality assurance requirements, digital twins help to maintain the quality control of the items being produced in an industry that is very bureaucratic when it comes to product quality assurance.
- **Cross-Industry Applications:** Therefore, usage of digital twins has to do with the capacity to design such approaches for doing active maintenance and performance optimisation of physical systems that can be constantly monitored and analysed. This leads to high performances and much time is not wasted on performing tasks that do not need much input.

This is why the efficiency that comes by having digital twin technology as a result of enhanced operations, plus, well enhanced decision-making, is the reason why organizations are seeking to embrace digitization. Thus, if the proprietary market did grow in lockstep, it could be assumed that the related digital twin market might also increase, extrapolated estimates suggest it could maybe be as much as $48 billion by 2026 (Fortune Business Insights, 2024).

Thus, a digital twin refers to a digital model of an object that makes use of several modern technologies to extend the level of optimization, provide prognostic functions, and improve understanding of the actual physical environment. They are a key technology in the age of IoT and AI-driven innovation because of the vast array of industries in which they have potential applications.

1.3 Purpose and Scope

As digital twin technology has the ability to change an extensive variety of industries and applications, its purpose and scope are broad as well as varied. A brief overview of the purpose and scope of digital twins are as follows:

- **Purpose of digital twins:**
  - In their practical application to design and testing, digital twins make it possible to create extremely accurate replicas of physical entities, events, or structures. With such models, analyses, as well as simulations and experiments, can be carried out. Digital twins may replica industrial processes, for instance, in manufacturing to find and improve errors.
  - Physical entities can be monitored in real-time due to DTs. This information is performance/ health or the state of the asset where the organizations can get real time data of the physical through sensors and feed it to the digital twin. This is particularly the case with reference to the preventive maintenance as well as the general management of the operations.
  - Thus, they are important in predictive analytics because of this same feature which helps the digital twins to predict events that are yet to happen in the real world. They can predict the possible subsequent steps and reveal some potential problems, and hence, contribute to enhancing the decision making of companies' actions based on trends analysis and real-time information. They are able for instance, to forecast a change in the climate or lack of success in equipment or presence of flaws in products.

- DTs help the decision-makers to get an insight of various systems in an organisation. Scenario: They offer a background on which you look at different events and analyse the outcome that results from various choices. This assist in coming with relevant decision making that with information that has been gathered.
- Therefore, the actual idea of digital twins is optimization so it can be discussed as the way of least cost. For example, in the utilization of the energy, sector of digital twins can be explored for better energy use resulting in less expenditures with the added advantage of impacts to the environment.

➢ **Scope of digital twins**

- Advanced twins are broadly utilized in fabricating, where they can screen machines, re-enact generation lines, and increment prepare proficiency. They are utilized in prescient support, item plan optimization, and quality control.
- Control plants, network systems, and renewable vitality establishments can all be demonstrated utilizing advanced twin innovation. This encourages prescient upkeep, vitality dissemination optimization, and vitality administration.
- Virtual representations of whole cities are made conceivable through the utilization of computerized twins. Information with respect to the environment, open administrations, activity, and foundation are all spoken to in these different shapes. They encourage the creation of well-informed choices by urban organizers for feasible advancement and progressed quality of society.
- Computerized twins are utilized within the healthcare industry to make patient-specific models and re-enactments. They can bolster pharmaceutical improvement, therapeutic gadget plan, and treatment arranging. They upgrade persistent results and bolster individualized pharmaceutical.

- Exactness horticulture is one field where advanced twins are valuable. Agriculturists may optimize water system, fertilization, and bother administration with their help by utilizing these models of areas and crops. Higher edit yields and less asset utilization are caused by this issue.
- Computerized twins are utilized by the flying industry to track the state of air ship frameworks and components in genuine time. Effectiveness in support and security are moved forward by this.
- Computerized twins are utilized to arrange and manage building ventures within the building industry. Office administration, quality confirmation, and extend administration are all encouraged by them.
- Coordination's and cost-saving measures can be accomplished by ventures by streamlining their supply chain forms through the displaying and optimization of computerized twins.
- Advanced adaptation of twins is utilized by natural offices to screen and figure changes in climate designs, environments, and common calamities. It is basic to have this information for both natural conservation and fiasco planning.
- Computerized twins are utilized in training as guidelines assets. Experts and understudies can communicate with virtual representations of perplexing frameworks and strategies much appreciated to them.

As innovation creates and more segments realise the potential benefits of computerized twins, their utilise is continuously developing. Advanced twins are getting to be an basic component of modern operations and decision-making, whether it is for streamlining fabricating forms, improving healing centre care, or building more maintainable cities.

1.4 Understanding Digital Twins

Understanding advanced twins requires understanding the concept of virtual copies of real-world things and operations. This specialized system coordinating the computerized and physical universes for real-time observing, examination, and re-enactment. The building, healthcare, development, genuine bequest, and agribusiness businesses utilize computerized twins. Building employments advanced twins for prescient support, execution checking, and item plan advancement. They upgrade customized treatment and mirror healthcare forms. By improving extend administration and office operations, advanced twins offer assistance the genuine bequest and development businesses with resource efficiency, crop production optimisation, and precision farming, digital twins in agriculture help. This unique method helps boost efficiency and innovation by analysing complex systems.

Classification of Digital Twins

Due to their many uses, digital twins are categorised. Digital Twins in Engineering support structural maintenance, manufacturing optimisation, and product design; in Healthcare, they aid patient-specific diagnosis and surgical planning; and in Other Industry Applications, they support smart cities, retail, energy, agriculture, and environmental modelling. Integration with IoT and Cyber-Physical Systems connects the virtual and physical worlds; Simulation and Predictive Modelling permits future scenario studies; and Real-time Process and System Monitoring gives insights and predictive maintenance. These categories demonstrate how adaptable digital twins may be used to many sectors to enhance decision-making and production.

1. **Digital twins in Engineering**

The engineering industry has played an important role in coordinating the complicated equipment's design, manufacture, and maintenance. The main source of this difficulty is the complexities involved in creating accurate physical models for such complex equipment. Integrated operations and maintenance are clearly needed in engineering practice. This requires keeping an eye on how the equipment is being used, sending out prompt alerts for potential problems, controlling the activation and deactivation of control systems, giving feedback on the state of maintenance, and visualizing maintenance procedures (Yang Fu, 2022).

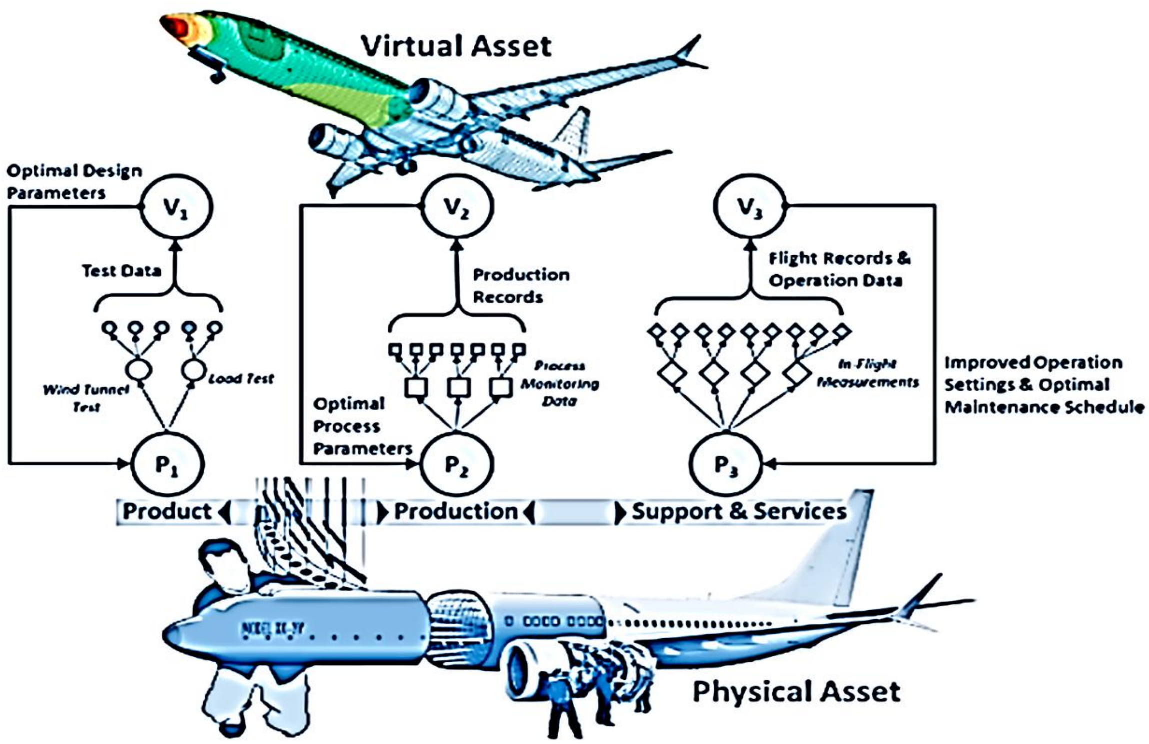

Figure 3: Use of Digital Twins in Engineering (Source: Loaiza 2023)

Due to the advancement in technologies such as the Internet, virtual reality VR, and augmented reality (AR), the design construction, and life cycle of mechanical equipment have been transformed. Thus, research and development of intelligent integration technologies for mechanical systems and equipments that is sustainable is meaningful. This involves creating an efficient industrial equipment design, manufacture, and maintenance platform that is quick, effective, and visually appealing (Fei Tao; He Zhang, 2019).

A possible solution is provided by the newly developed idea of digital twins. Engineers can receive input in real time from the virtual world because of digital twins. Engineers can make well-informed maintenance decisions by combining this feedback with information from expert databases. The engineering processes' time and expense are greatly decreased by this integration. Engineering may become more productive, convenient, and cost-effective by simply incorporating digital twins into equipment design, manufacture, and maintenance. This will make it possible to manage in-service equipment and create new products more effectively.

Applications in Engineering

The applications in Engineering that involve in digital twin are as follows:

- ✓ **Product design and development**

The primary stage of any physical product's life cycle is development and design of the product. This stage involves converting concepts into concrete, ready-to-sell goods that satisfy consumer requirements. In order to develop successful goods, this approach combines creativity, engineering know-how, market research, and continuous testing (Ruzsa, 2020).

Essential Phases of Design and Development for Products:

- **Idea generation:** It is the first step in the process. Various sources, such as market trends, customer feedback, or internal innovation initiatives, can provide these ideas. The goal is to find a product concept that addresses a market demand or problem.
- **Market Research and Analysis:** After a concept has been selected, an extensive market study is carried out. Understanding the competition, the target advertises, and estimating techniques are vital for this also advertise designs. Looking at the capacity of the thought and it advertise request is the objective.

- **Concept Advancement:** The item concept is refined taking after in-depth examination. Deciding the characteristics, utilitarian components, and plan of the item falls beneath this category. Together, engineers and architects create designs that fulfill both innovative requirements and client expectations. These designs can be advanced representations made with CAD software or actual models.
- **Prototyping:** Building item mock-ups or models is another Testing and plan advancement are made conceivable through prototyping.
- **Plan Emphasis:** Model input is utilized to educate essential plan alterations amid this stage. To ensure that they fulfil specialized and client criteria, the product's highlights, looks, and usefulness are persistently progressed.
- **Building and Fabricating Arranging:** After the completion of the plan, engineers draft total fabricating plans. This covers the choices of crude materials, fabricating procedures, and quality confirmation strategies.
- **Testing and Approval**: In arrange to create beyond any doubt that items satisfy quality and security measures, they experience broad testing. Various tests, counting client encounter, execution, and stretch tests, are included in this stage.
- **Generation and Fabricating:** After the plan has been confirmed, the item moves on to the fabricating arrange. Typically, where large-scale fabricating takes put. In arrange to guarantee item quality, supply chain administration and quality control are fundamental.
- **Launch and Showcasing:** The item is prepared to be discharged into the showcase. To advance the item to the planning gathering of people, showcasing strategies are developed.
- **Post-Launch Bolster**: After the product's discharge, there's ceaseless support, client back, and overhauls accessible.

Role of Technology:

Modern product development and design depends completely on technology. Technology such as digital prototyping, 3D printing, simulation software, and computer-aided design (CAD) have completely changed the process. Real-time checking and virtual prototyping are moreover made conceivable by the integration of computerized twins, which increments efficiency and brings down costs.

In conclusion up, planning and creating a product may be a complex handle that requires advancement, capability in innovation, an understanding of the showcase, and ceaseless testing. The utilize of innovation, like computerized twins, has changed the strategy in which merchandise are conceived and brought to life, and it's a pivotal organize in bringing effective things to showcase.

- ✓ **Production and Manufacturing:** These two are the fundamental processes through which raw materials undergo metamorphoses into finished products. With design, production, assembly and control, this dynamic process encourages technical and economic evolution in countless fields of industry.
- ✓ **Asset Management:** Since assets have a life cycle they need to be managed correctly. Asset management is an important branch of managerial science. This includes financial assets, non-physical assets such as trademarks, patents and physical assets including machinery. This is because organizations may attempt to improve their operational, maintenance, disposal, and distribution cycles with the aim of increasing efficiency and decreasing disruptiveness in an effort to satisfy the market.
- ✓ **Predictive maintenance:** In order to avoid the failures of equipment that are inevitable, then there is the use of data sensors and machine learning known as predictive maintenance. Besides, it incorporates current and past information to

maintain equipment only when it is necessary lowering costs, eliminating-surprise stoppage periods, and increasing the useful lifespan of the assets. Through this strategy, the exercise of maintenance changes from being necessarily reactive to being proactive.

- ✓ **Process Optimization:** Operational processes are systematically improved for efficiency, reduced waste, and enhanced performance through process optimization. Whether in the supply chain, manufacturing, or service industries, it involves evaluating and improving workflows to increase efficiency, reduce costs, and satisfy customers. Process optimization is essential for continued progress and competitiveness in a time that demands adaptation.

2. Manufacturing and Production

Manufacturing holds a place among the most driving industries in the digital twin revolution. Digital twin has changed the industrial sector and introduced the new approach of smart production, better supply chain management and better quality assurance. This comprehensive research delves extensively into a variety of manufacturing applications to illustrate the significant influence of digital twins on the sector (Satish Kumar, 2020).

- ✓ **Smart Manufacturing**

Smart manufacturing, commonly referred as a Industry 4.0, represents a significant change in the field of production. It is defined by the incorporation of digital technologies into production procedures, resulting in operations that are extremely effective, flexible, and data-driven. Digital twins are crucial to the idea of smart manufacturing (Kusiak, 2023).

Essential Elements of Smart Manufacturing:

- **Digital twins:** Such real-time, predictive tools are available for manufacturing processes and equipment. They focus on the effectiveness of the equipment, forecast maintenance requirements, and optimize production schedules.
- **IoT Devices:** integrated into machinery, IoT sensors and devices gather data on elements like vibration, pressure, and temperature. The digital twins are fed with an endless supply of data from these devices.
- **Big Data Analytics:** Big data analytics techniques handle huge quantities of data produced by smart manufacturing. They provide decision-making ideas, identify trends in past data, and analyse it.
- **Machine Learning:** By using real-time data, machine learning algorithms can optimize production and forecast equipment faults. They facilitate independent decision-making and ongoing development.

Quality Control: Using Digital Twins to Ensure Excellence

One of the most important aspects of quality control in the production process is making sure that goods meet predefined standards and specifications. Digital twins have revolutionised quality control because they provide predictive analytics and real-time monitoring (Ruiping Luo, 2023).

Essential Elements of Quality Control:

- **Digital twins:** Digital twins of goods and manufacturing procedures offer in-the-moment monitoring and can identify departures from quality requirements. Additionally, they forecast when repairs or modifications are required.
- **IoT devices and sensors:** Sensors built into equipment and products gather information on dimensions, temperature, and material characteristics.

- **Machine Learning:** By analysing data from digital twins, machine learning algorithms can forecast flaws and quality problems in real time.

✓ **Supply Chain Optimization**

Supply chains are complicated systems with a lot of components that move, stakeholders, and other variables. Supply chain management has experienced a change due to digital twins, which offer real-time insight, predictive analytics, and improved decision-making powers (TAŞKIN GÜMÜŞ et al., 2018).

Key Elements of Supply Chain Optimization:

- **Digital Twins:** The real-time tracking, monitoring, and estimating can be done with digital twins of the total lifecycle of supply networks or just definite fragments of it.
- **IoT Devices:** Any supply chain will require IoT sensors to monitor the whereabouts and state of the machinery and the raw materials. Such sensors allow real time monitoring, in order to optimize visibility of resources and excellent, as well as security and efficiency. Smart IoT things are supposed to enhance the processes and introduce better decision-making options in delivery, manufacturing, warehousing, or transportation market spheres.
- **Big Data Analytics:** Big data solutions capture relevant performance information on the supply chain, as well as potential areas for enhancement, through digital twin data and data from connected devices within the IoT. These analytical tools process and summarize the large information and look for patterns in the supply chain. This allows for better decision making, operational improvements, cost savings and efficacious operation in the supply chain. Companies are likely to stand out or perform better in supply chain through the use of big data analysis.

3. Digital twins in healthcare

Digital twins, or DTs, have already had a big impact on a lot of different industries, including automobile, aerospace, and construction, and manufacturing. But the field of healthcare, especially in the field of precision medicine, is one of the most promising areas for DTs. Its effects could hardly be more innovative (Armeni & Irem Polat, 2022).

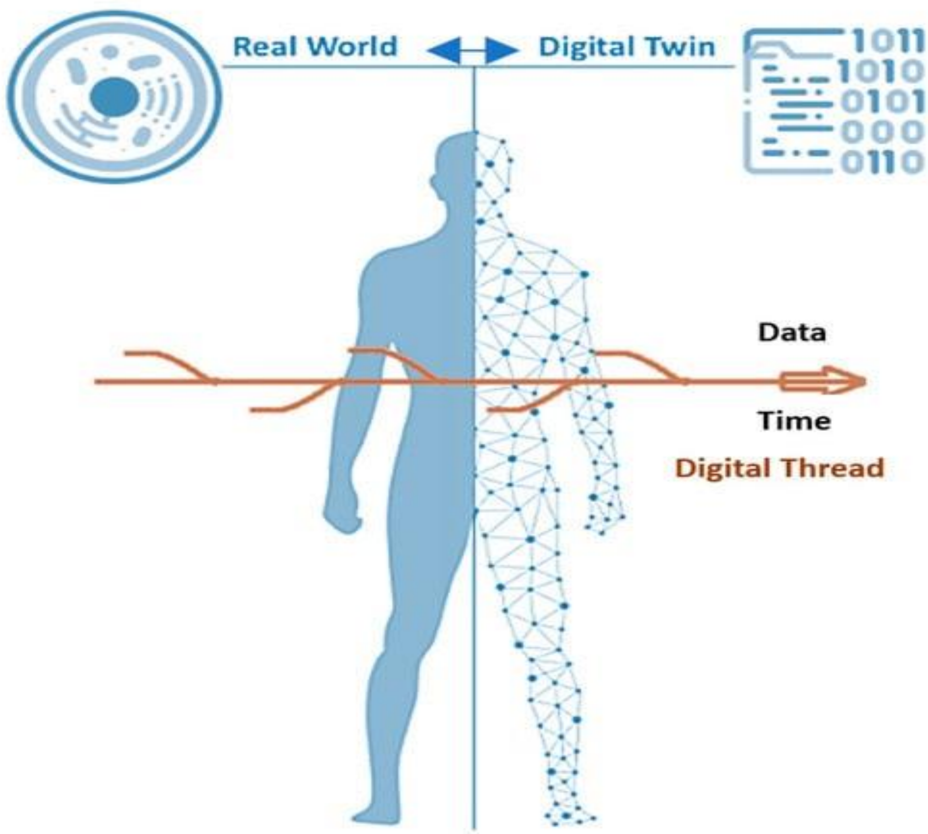

Figure 4: Interaction of real world and digital twin (Source: Maged N. Kamel Boulos 2021)

In the healthcare business, a digital twin (DT) is a virtual depiction of a physical entity or process, such as people, their anatomical structures, and entire hospitals. Current healthcare DTs are broad and dynamically combine data from numerous sources. EHRs, disease registries, physical indicators, demographic data, developing lifestyle data, and "-omics" data (genomics, biomics, proteomics, and metabolomics) are included.

Rapid expansion of foundational technologies like AI and the IoT has boosted DTs in healthcare. These technologies enable the collection of increasingly diverse, accurate, and accessible data, including biometric data, behavioural patterns, emotional insights, cognitive data, and psychological profiles (Mohsen Attaran, 2023).

Applications of DT in healthcare have an impact that becomes more than the present situation. It aligns with the broader precision medicine movement, which aims to increase the healthcare system's efficacy and efficiency. The traditional "one-size-fits-all" approach to therapy is being replaced with a more individualised strategy that takes inter-individual variation into account. Personalised medicine, another name for precision medicine, is centred on the accurate administration of treatments and diagnostics that are customized to each patient's distinct genetic, biomarker, phenotypic, physical, and psychological traits. Delivering treatments that are not only accurate but also administered to the right individual at the right time is the ultimate aim (Haleem et al., 2023).

4. Digital twins in Construction and Real Estate

Digital Twins, which are virtual replicas of tangible assets, can improve resource and project management in construction and real estate." BIM, a popular building technology, provides static data with dynamic, real-time information. Digital Twins do the same. BIM offers digital prototypes of the structure and construction project with functional and physical properties. The sensor-equipped real-time data of Digital Twins enables construction managers, designers, and clients to monitor projects. This real-time knowledge helps construction teams to visually track the progress, see the problems that might occur, implement needed changes to achieve quality and timely completion of projects while maintaining safety and cost constraints (Hossein Omrany, 2023).

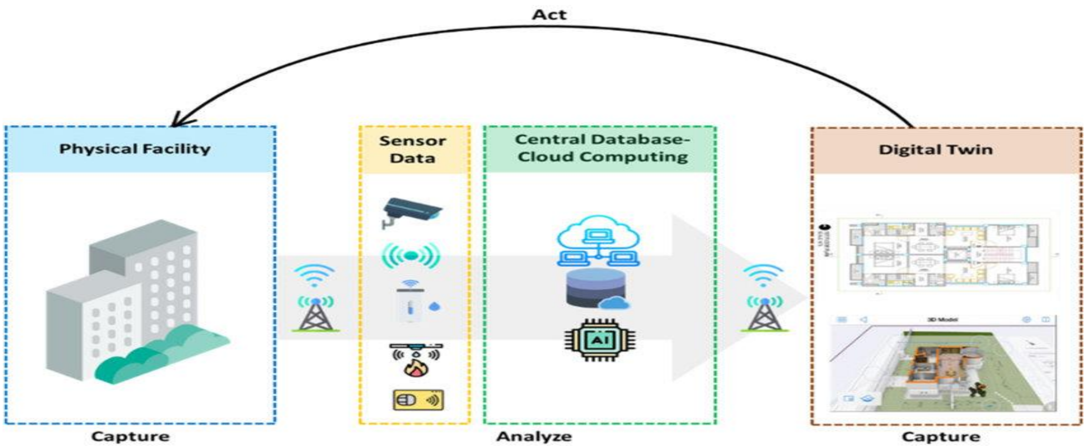

Figure 5: Building Information Modelling (Source: Jazzar et al., 2020)

Moreover, digital twins are useful in the construction sector for purposes other than project tracking. They support resource planning and logistics, support in safety management, and assist in the monitoring of a variety of resources, including labour, materials, and equipment. Digital Twins give real estate agents and property owners a thorough understanding of physical assets, facilitating the collection and analysis of information on an asset's performance and state (Zahedi et al., 2024).

That being the case, it is expected that the employ of digital twins built on smart infrastructure in the construction and real estate industries will unlock new levels of efficiencies relative to cost, time, sustainability and safety on projects. Digital twins are an adaptable and priceless instrument for the construction industry that expands the possibilities for project and asset management in various fields."

5. Digital Twins in Agriculture

In agriculture, technology is increasingly becoming a crucial advantage, bridging the gap between traditional practices and state-of-the-art innovations. The word "agriculture" refers to a wide range of practices, from traditional agricultural methods to innovative methods like aquaponics, each with its own set of difficulties. Technology is essential to understanding the complexities of the multi-scale settings that agriculture incorporates as it develops. The integration of digital twins, which function as a digital representation of agricultural entities and processes, is one notable accomplishment. By making it easier to digitize knowledge about both established and new farming techniques, these digital twins open new avenues for efficient supply chain management and food production in the future (Warren Purcell, 2023a).

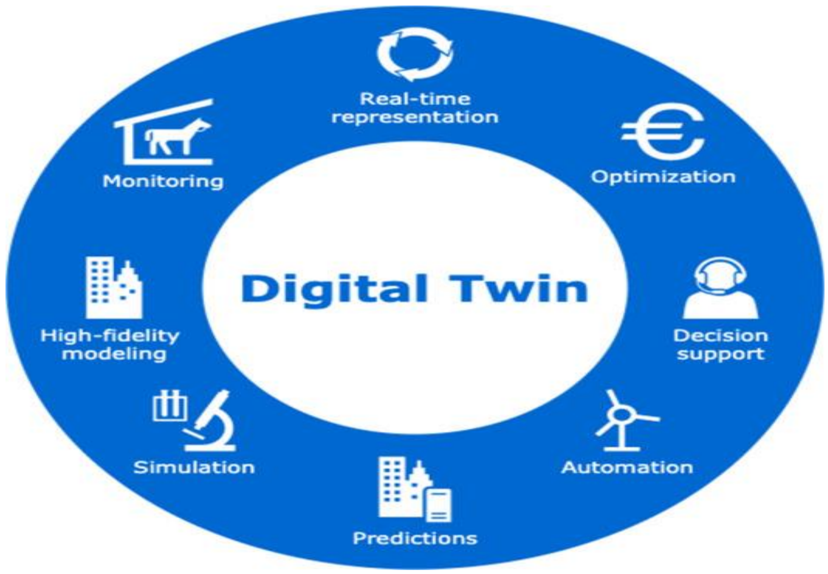

Figure 6: Digital twin application in real world (Source: T. N. Warren Purcell 2023)

Digital twins supply an essential way to expected agricultural advancement. Digital Twins use high-fidelity models, what-if simulations, IoT, and Cyber-Physical Systems to help farmers assess, understand, and optimise their agricultural units. These helps identify and control external and internal variables that affect entity health and production. Real-world applications of digital twins in programmes like the European Union's Smart Agri-food and Fractals initiatives show their benefits in agricultural use cases. However, existing literature still faces challenges, emphasising the need for continued research and creativity in this innovative field (Nikolaos Peladarinos, 2023).

Types of Digital Twins

Digital twins, which are often identified on the basis of whatever they obtain for, are essential to many different companies and are transforming our perception of and interactions with the real world. The several sorts of digital twins are covered in this section.

- **System Digital Twins**: This includes Entire Ecosystems Whether it's a manufacturing facility, smart city, or complex industrial environment, system digital twins represent whole systems. With the ability to depict the interdependence and links between different parts of the system, these digital twins provide an integrated perspective. System digital twins allow firms to improve operations, boost productivity, and effectively predict difficulties by analysing the complete ecosystem.
    - **Uses:** System digital twins are used in manufacturing to track equipment status, optimise production lines, and enhance supply chain logistics. They make emergency preparedness, efficient energy management, and optimized traffic flow possible in smart cities.
- **Digital Twins for Products: Emphasizing Individual Entities,** Product digital twins focus on specific physical things, from consumer goods like cell phones and appliances to complex machinery like cars and airplanes. These are digital replicas of physical objects which mimic actions and characteristics; with their help, comprehensive analyses, design verifications, and prognosis of maintenance needs are feasible.
    - **Uses:** Item advanced twins are utilized within the aviation industry for confirming air ship plans and estimating upkeep necessities. They are utilized by the car industry for quality control to spot imperfections early within the

generation prepare. They make prescient upkeep conceivable for shopper items, ensuring their constancy.

- **Computerized Twins for Forms:** Expanding Generation Adequacy, prepare advanced twins are mechanical and fabricating prepare recreation and replication devices. Through their arrangement of real-time experiences into prepare operations, they empower companies to improve their generation forms, boost vitality effectiveness, and distinguish support needs. In segments where operational viability and handle optimization are basic, handle computerized twins are priceless.
- **Employments**: Prepare advanced twins are utilized in fabricating to optimize production processes, recognize issues, and progress asset effectiveness. Within the vitality division, they screen and optimize the yield of vitality whereas lessening squander and progressing maintainability.
- **Computerized Twins for Resources**: Improving Resource Lifecycle, Person resources, such as apparatus, hardware, or foundation, are the subject of resource computerized twins. The digital twins offer an extensive virtual representation of the asset, including its design, maintenance records, and current operational information. Asset digital twins enable businesses to extend the life of their assets, maximize their performance, and cut downtime by using predictive maintenance.
    - **Uses:** Asset digital twins are useful in sectors where machinery dependability is essential. They guarantee that manufacturing equipment runs as efficiently as possible, reducing downtime. They enable predictive maintenance of infrastructure in services, improving reliability and reducing costs.

⇨ **Network Digital Twins: Increasing Interaction,** Supply chains, transportation systems, and communication networks are just a few examples of the complicated networks in which digital twins simulate. Organizations can use them to optimize routing, boost reliability, and enhance overall network performance since they capture the interactions and relationships within the network.

- **Uses:** Network digital twins are used in telecommunications to forecast congestion sites, improve connectivity, and optimize the transmission of data. Supply chain industries use them to ensure on-time delivery, improve logistics, and save reduced transportation expenses.

⇨ **Human Digital Twins: Enhancing Personalized Experiences,** defined as virtual avatars of real people, human digital twins are expected to analyse data concerning an individual's physiology, behaviour and lifestyles. These "digital twins" are crucial for enhancing treatment plans that apply to the individual, predicting possible health-related problems and enhancing efficiency of the treatment.

- **Uses:** Healthcare is among the industries that benefit from human digital twins through the use of the following applications: The selves susceptibility, the treatment plan, the treatment commitment and the disease risk. They are also equally relevant in wellness and fitness as they assist people to meet their health goals.

⇨ **Environmental Digital Twins:** Encouraging Sustainability, the environment offered by digital twins is the natural ecosystems, climatic phases, as well as the environmental factors. These digital twins provide the appropriate data regarding shift in environment and enable organizations and decision players for promoting sustainable measures and lessening the impact of climate change.

- **Uses:** The aforementioned components of sustainability in planning—environmental preservation, energy efficiency, and carbon emission reduction—are made feasible by the use of environmental digital twins in urban design. They also help in matters of farming, thus helping to make water use efficient as well as equipment which enable precision farming.

⇨ **Mixed-Reality Digital Twins:** Improving User Engagement, Users can engage with both digital and physical aspects at the same time with mixed-reality digital twins, which combine both virtual and augmented reality technology. These immersive experiences provided by these digital twins allow for improved collaboration, training, and visualization across a range of industries.

- **Uses:** Mixed-reality digital twins in manufacturing help with virtual assembly training, which enhances worker proficiency and reduces rate of errors. They are also employed in architectural design, enabling clients and architects to engage and visualize building designs prior to construction.

Key components and Technologies

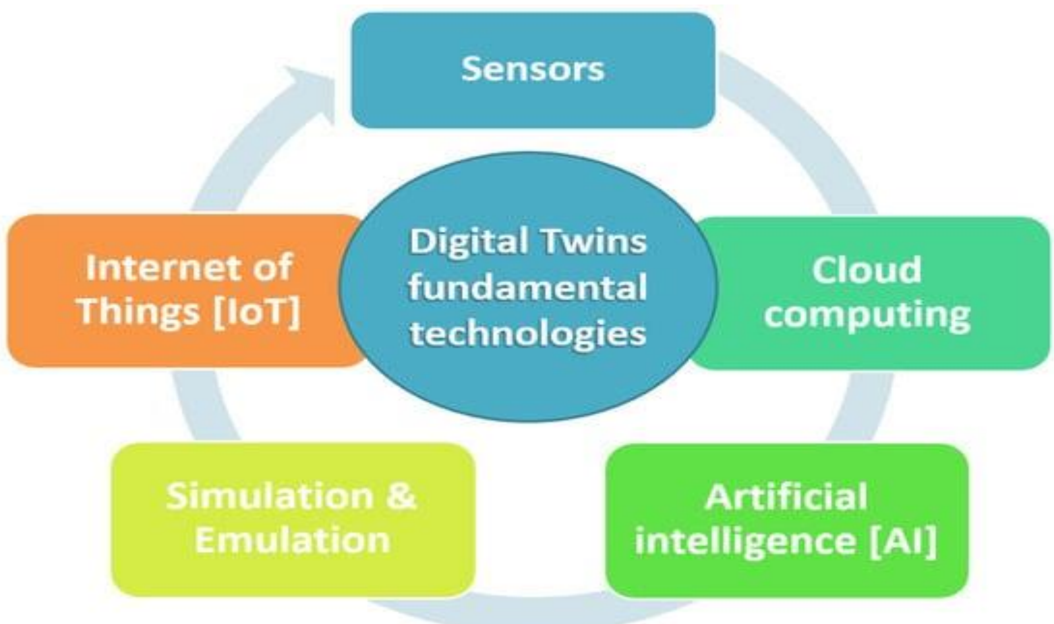

Figure 7: Key components and technologies (Source: Dimitrios Piromalis and Antreas Kantaros 2022)

A number of essential components are combined to create digital twins. Real systems or objects are represented by actual objects, and 3D modelling and simulation tools are used to create virtual versions of them. IoT sensors make sure the digital twin faithfully replicates the thing by collecting data from it in real time. Cloud computing has the scalability to handle the vast amounts of data produced. Analytics reveals patterns and insights from huge data. Machine learning and AI improve digital twins with predictive maintenance and optimisation, while simulation software allows scenario testing. With the help of communication protocols and visualisation tools, data exchange is simple. Manufacturing, healthcare, urban planning, and predictive maintenance are just a few of the industries where digital twins, which offer real-time digital representations of physical objects and systems, have broad uses. Therefore, data-driven decisions are possible (Maninder Jeet Kaur, 2020).

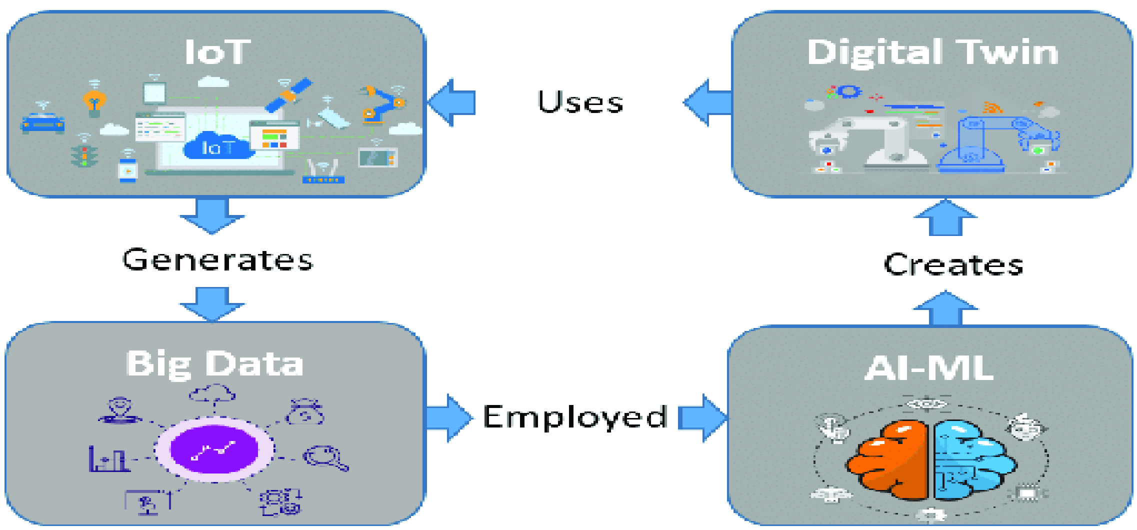

Figure 8: Data flow of participant in digital twin (Source: Rathore 2021)

- **Sensor Network**

Sensor networks are becoming a basic technology with significant applications in many different fields in an increasingly interconnected society. These networks are advantageous in the IoT because they provide the means to acquire information from physical objects and convert it for use by digital devices. This article will highlight the concept of sensor networks, fundamental components worth knowing, and some of the major niches, such as industrial automation, smart city, healthcare, and environmental niches.

The Components of Sensor Networks

Sensor systems are built on sensor hubs, which are small, generally affordable devices with a variety of sensors that may gather data from their surroundings. Temperature, stickiness, weight, movement, light, and other variables are among the variables that these sensors can measure. These sensors can be applied to a variety of tasks due to their adaptability. The purpose of placing these sensor hubs around the area of interest is to create an arrangement.

Uses:

- **Environmental Monitoring:** Metropolitan zones, woods, and environments have sensor systems to screen natural conditions. They offer assistance researchers and specialists collect temperature, mugginess, discuss quality, and other information. This information makes a difference clarify discuss contamination, climate alter, and other natural issues.
- **Industrial Automation:** Made strides manufacturing and industrial forms require sensor systems. They screen apparatus weight, temperature, and work for prescient upkeep. Checking these components in genuine time can boost efficiency and decrease downtime.
- **Healthcare:** Medical sensor networks monitor patients digitally. Sensor-equipped devices provide medical experts patient vital sign data. These real-time data allow patients with chronic conditions to obtain continuing treatment and early intervention.

- **Smart Cities:** Sensor networks are key to smart cities. Smart energy networks, trash management, and traffic control use them. Enable dynamic traffic routing and collect congestion and traffic sensor data to cut commutes and fuel. Waste management sensors save resources and reduce emissions by optimising trash pickup schedules by fill level. Smart energy grids monitor and control electricity distribution with sensing networks.

➢ **Internet of Things (IoT) Devices**

The approach we interact with our environment and conduct business has changed due to IoT (Internet of Things). In general, the meaning of the Internet of Things involves a connection of multiple devices that are included to work on the Internet with the Transmission Control Protocol and the Internet Protocol. These gadgets include vital medical equipment like insulin pumps and pacemakers as well as commonplace home appliances like smart thermostats and refrigerators. IoT devices improve automation and connectivity by enabling information to move between items. This device network serves as the cornerstone for the Internet of Things revolution.

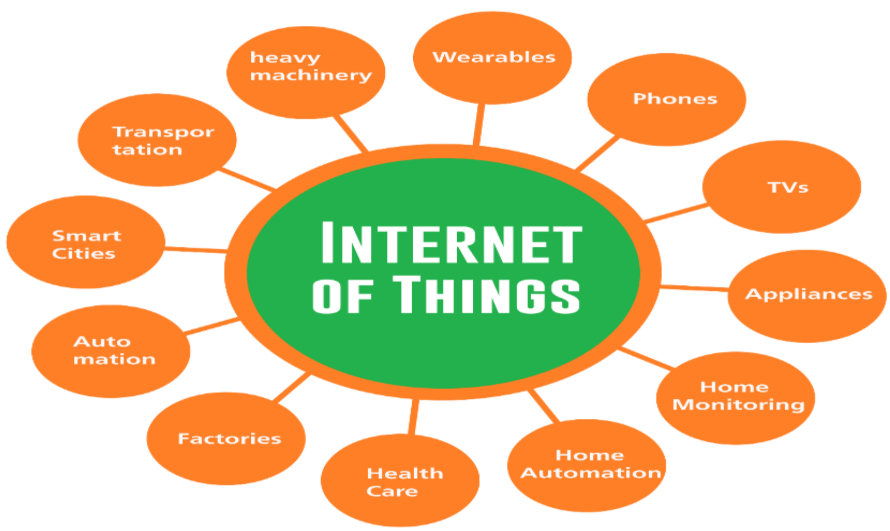

Figure 9: Internet of things and its use in real world (Source: andrewshaw 2021)

IoT has been around for a while, but it's still considered fresh and emerging. IoT has been around for a long in numerous incarnations, but a few significant factors have contributed to its recent success. The ubiquitous use of smartphones and tablets has helped the Internet of Things evolve quickly. With the emergence of Wi-Fi and cellular networks, linking devices has become easier. Due to falling CPU, sensor, and networking device prices, enterprises may now afford Internet of Things solutions. These factors plus customer desire for smart and connected devices have made the Internet of Things a vibrant ecosystem (Nižetić et al., 2020).

- **Impact of IoT on business**

The rise of IoT has changed corporate landscapes. Many industries are adopting IoT to acquire massive amounts of data about customers, products, and processes. This vital data helps organisations enhance efficiency, procedures, decision-making, and product and service quality. IoT-enabled machinery sensors capture real-time data on use and performance for predictive maintenance in production. IoT devices in healthcare provide remote patient monitoring. IoT in smart automobiles enables real-time diagnostics, safety features, and V2V/V2I connectivity, which are essential to autonomous transportation systems. In addition to businesses, IoT benefits consumers. It boosts involvement, connection, and environmental awareness (Sharma, 2020).

➢ **IoT Application in Engineering Fields**

- **The Internet of Things' Impact on Engineering:** Numerous technical fields, including the creation of smart vehicles, manufacturing, healthcare, and environmental monitoring, are significantly impacted by the Internet of Things. The implementation of IoT in various fields has resulted in huge data collection, which has prompted the creation of data analysis tools for defect detection and predictive maintenance. The Internet of Things and engineering are combining to create a force which is changing a lot of sectors (Nazem Zermani Amen, 2022).

- **Digital Twin Technology:** This technical technique supports the Internet of Things. A digital twin in essence is a virtual replica of real-world objects and processes. As a real-time monitoring, modelling and even predictive maintenance system, it describes the link between the digital and the physical. Digital twins are essential in areas of performance and reliability that must be attained to ensure that engineered processes are implemented optimally. This ability to model and characterise the behaviour of manufacturing machinery helps to enable both predictive maintenance and time saving via digital twins. Digital twins help prepare surgical procedures and therapies by simulating patient-specific conditions. Engineers and decision-makers benefit from digital twins' data-driven resource allocation and maintenance insights.
- **IoT in Engineering Benefits:** In this regard, IoT present several benefits to engineers and the engineering profession in general. Preventive maintenance and real-time decision making can only be made with the help of remote monitoring. Wearable device produces real-time information regarding the status of the machines and through the interaction of IoT, predictive maintenance, less down times and lower costs are realized. Furthermore, IoT technologies enhance product and service delivery, safety, and reliability.

IoT devices are part of our daily lives and affect several engineering fields. The convergence of IoT and engineering could improve variable speed pump reliability, efficiency, and cost. However, to fully realise IoT's revolutionary potential and ensure its responsible and secure adoption, its difficulties and ethical issues must be addressed.

- **Cloud Computing**

Cloud computing (CC) has become a key technology that supports a number of innovations. Because of its ability to adapt as an important information and technology, academics have been engaged by it, which has encouraged the development of sustainable Cloud systems. With the ability to handle information, apps, and data in a seamless manner across a variety of contexts, this new generation of services transforms accessibility. At the same time, massive datasets, or Big Data (BD), are being produced as the Internet of Things (IoT) expands rapidly. Big Data, cloud computing, and the Internet of Things are all being used together to transform the technology landscape and open up new avenues for integration and innovation.

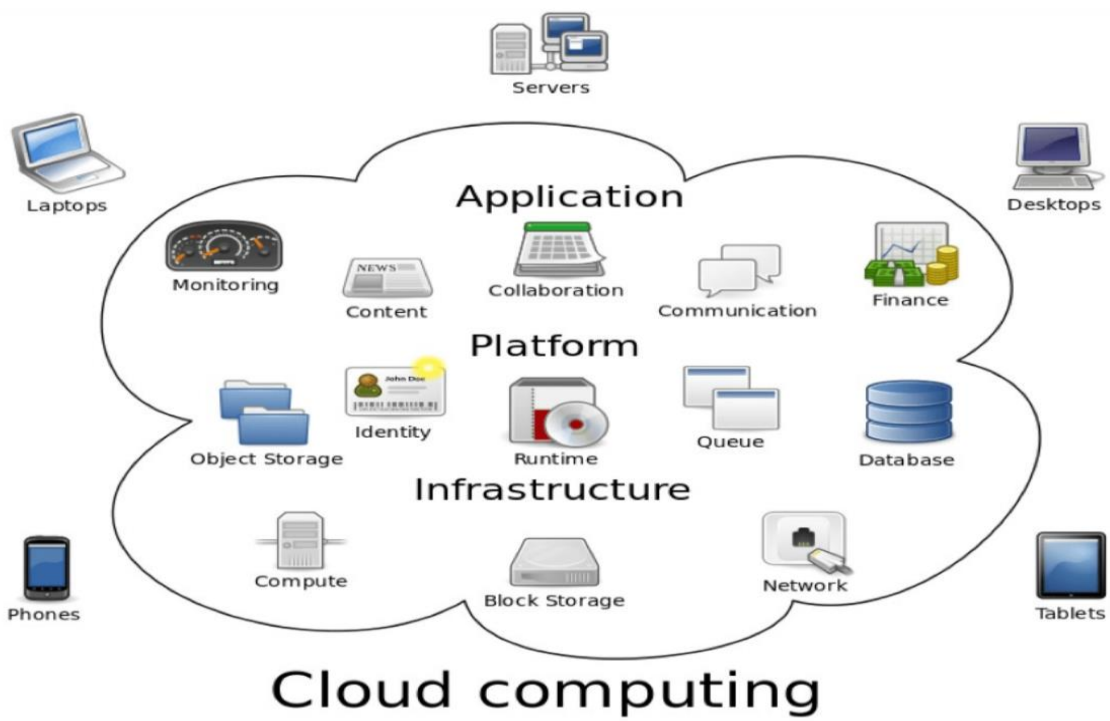

Figure 10: Cloud computing and its participant (Source: Mohammed Al Masarweh 2022)

This research project examines the complex interactions between Cloud Computing (CC), Big Data (BD), and the Internet of Things (IoT). To better understand the inherent security and management challenges associated with these technologies, it first analyzes the fundamental properties of CC and BD as derived from IoT. By evaluating their shared characteristics, the study uncovers new insights and potential integration strategies, envisioning a sustainable ecosystem within a Digital Twin framework.

- **The Function of Cloud Computing in Internet of Things-Based Big Data**

Understanding the relationship between Cloud Computing (CC) and IoT-generated Big Data is a key focus of this research. By emphasizing improvements in security and privacy, this integration addresses a significant academic gap. With CC serving as the backbone, the influx of data from IoT devices is efficiently managed. Experimental data are presented to validate the effectiveness of the proposed model, utilizing encryption methods such as RSA, RC5, and AES. In addition to expanding the potential of CC and IoT-based Big Data, this model establishes an innovative and scalable service platform. The study highlights the enhancement of privacy and security measures to align with the evolving demands of the networked digital world.

- **A New Security Algorithm Proposal**

Information conducts a comprehensive analysis of existing security challenges within the integrated Big Data (BD) and Cloud Computing (CC) framework. Upon identifying these limitations, it proposes a novel security approach designed for long-term cloud systems, incorporating digital twin technology. Within this complex environment, the proposed algorithm aims to enhance data privacy, confidentiality, and integrity, reinforcing security measures in cloud-based ecosystems.

- **Big data analysis**

Smart cities are becoming dynamic urban ecosystems in the era of the Internet of Things (IoT). Big Data Analysis (BDA) is essential to transforming these cities into centers of effective data processing and excellent governance by allowing huge quantities of data to be generated.

Figure 11: Big data and its application (Source: Kaviraju 2022)

- **Digital Twins: An Idea That Could Change Everything**

In smart cities, digital twins, or DTs, are a novel idea. These are digital copies of real-world objects, infrastructure, or even whole cities. In the context of smart cities, DTs provide a real-time view for informed decision-making by reflecting infrastructure, transit networks, and citizen behaviour.

- **The Significance of Big Data Examination**

The transformation of smart cities is mainly driven by BDA. It makes advanced data analytics suitable by processing and interpreting the huge quantity of data provided by IoT devices. Convolutional Neural Networks (CNNs), one type of Deep Learning (DL) algorithm, are crucial for processing the big and complex datasets seen in smart cities.

- **Creating Digital Twins Real-Time Insights**

Data analysis is quickened by DL algorithms that are related with BDA. Since of the real-time experiences they offer, DTs are more responsive and valuable. Proactive issue tackling, asset optimization, and drift estimating are all helped by this real-time observing.

- **The Strategy of Distributed Parallelism**

DL algorithms' disseminated parallelism strategies move forward the effectiveness and speed of information preparing. They encourage provoke decision-making, which upgrades the administration of keen cities as a entirety.

- **Efficiency in Energy Use and Power Diversion**

The study's center on energy proficiency is imperative. In smart cities, productive power allotment and vitality administration are basic to the long-term reasonability of IoT-BDA frameworks. Control preoccupation issues are basic for vitality asset optimization.

- **Efficiency of Signal Transmission Energy**

A critical region of centre is vitality proficiency in signal transmission. The cautious utilize of vitality assets amid information transmission, which diminishes working costs and natural affect, is emphasized within the think about.

- **Optimizing Transmission of Data**

By keeping up data flow at the millisecond level, information transmission delays can be minimized by parameter optimization. This increments precision in information determining and moves forward responsiveness.

In smart cities, the combination of digital twins and enormous information investigation speaks to a modern time. It gives city directors and organizers the capacity to more successfully construct urban situations, speed up information transmission, move forward the exactness of information estimating, and inevitably boost the advanced advancement of smart cities. Urban living guarantees to be more secure, more productive, and more carefully controlled within the future due to these advancements.

➢ **Artificial intelligence (AI) and Machine learning**

In recent years, the digital twin technology is designed as a real-life application for modeling, building, and monitoring the organizations' systems and assets more effectively. To generate higher-order, elaborated, data-based depictions, it draws on combination of machine learning (ML) and artificial intelligence (AI) algorithmic approaches. In detail, AI and ML enhance precision, prognosis, and the continuous enhancement of actual-time actions' efficiency in DT. Artificial intelligence and machine learning are now progressing at the rate where they are revolutionizing industries and the way that people integrate technology and information. Hence, the aim of this research is to discuss the current and future application of AI and ML, pros, and cons, and the implications for various industries (Lv et al., 2022).

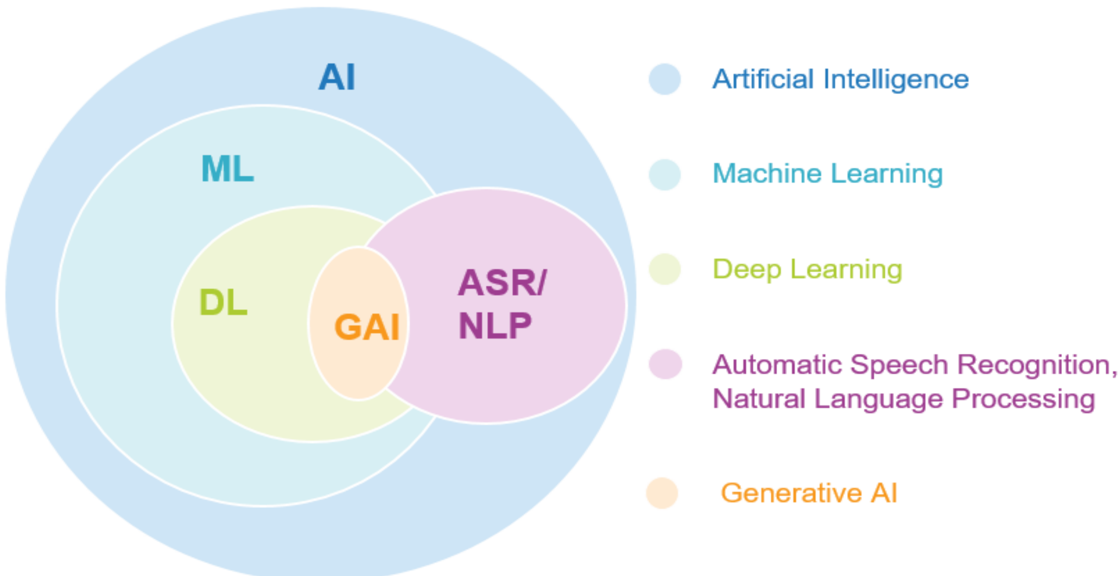

Figure 12: Ven diagram of artificial intelligence (Source: Anca Ralescu 2021)

- **AI and ML in Healthcare:** These two fields are rapidly progressing in the healthcare industry. They are used in predictive analytics, early disease detection, drug discovery, and medical image analysis. Massive healthcare datasets are being processed by ML algorithms, which are also helping to improve accuracy in diagnosis and tailor therapies for specific patients.
- **Natural Language Processing (NLP):** AI-powered NLP is changing how humans communicate through language. Artificial intelligence-powered chatbots, virtual assistants, and language translation services are evolving to improve customer service and communication. Additionally, significant to sentiment analysis and gratified ideas are natural language processing (NLP).

- **Autonomous Systems:** Autonomous systems such as drones and self-driving automobiles are part of the AI and ML systems. These are technologies that, in their ability to revolutionize logistics, transportation, and surveillance, work by using algorithms and real time data for path planning as well as decision making.
- **Finance and Trading:** In the financial field, risk evaluation, fraud identification, algorithmic buying and selling, and portfolio administration are conducted with the help of AI and ML calculations. These technologies extend the range of fintech technologies by basing investment decisions on historical and current patterns at the market.
- **Impact on the Environment:** AI and ML are involved in the capability of solving environmental problems. They offer means by which climate change and sustainability can be mitigated through accurate prediction of natural disasters, better usage of energy and resources among others.
- **Ethical and Privacy Concerns:** In AI and ML technologies, ethical and privacy concerns can be seen and are worth worrying about since the technologies are improving rapidly. These include issues such as errors in the algorithms and in the gathering and use of the data belonging to individuals. There are general principles that should be followed when applying AI systems, namely non-discrimination, explicability, and data protection.
- **Future Prospects:** The growth of machine learning and artificial intelligence will not cease. As with 5G networks, quantum computing and IoT, it sees the future AI age as an era of invention and relationships. These two areas of research—machine learning, reinforcement learning, and explainable AI—remain active, offering the possibility of even more significant advances in AI and raising the prospect of AI self-education.

Last but not the least machine learning and AI are revolutionizing the technical front for various organizations. There is no doubt about the overall capacity to improve procedures, elevate the level of judgement, and increase the standards of living. What you have to always bear in mind is that these advances come with some questions as to ethics and privacy. As AI and ML research and development continue further, the innovation and moral consciousness should work hand in hand for the welfare of the public. AI and ML are expected to positively contribute towards most of the applications including, environment and health, finance and a host of others, thus setting the tone for an even brighter future.

1.5 Advantages and challenges of digital twins

Digital twins have altered many industries with improved decision-making and predictive maintenance. Operational efficiency and real-time information spur innovation. Challenges include the need for many resources to construct models and data privacy risks caused by extensive use. An effortless integration is further hampered by industry-wide interoperability problems. The undeniable revolutionary potential of digital twins in changing operations and business strategies, despite hurdles, encourages continuing investigation and development.

Advantage of Digital Twins

A lot of sectors have been reshaped by the power of digital twins. Digital clones of physical structures offer status tracking, prognostic maintenance, and conservativeness. According to the information, digital twins enhance decision-making process, cost, and safety through collaboration and data driven innovation. These innovations promote efficiency, sustainability, and consumer satisfaction. Utilising digital twins in such procedures could alter how industries perform and maintain their assets.

1. **Real-time Monitoring and Analysis**

Real time evaluation of physical assets and their operations is facilitated by digital twins. It is constructed in a way that the actual system is modeled digitally and this model is updated constantly from data gathered from sensors and the like. For immediate decision making and action, efficiency and condition of real estate data is offered in this dynamic representation. Real-time monitoring is crucial in industries like manufacturing, healthcare, and smart cities where it's important to respond fast to changing circumstances (Mengnan Liu, 2020).

2. **Predictive Maintenance**

One of the major benefits of implementing digital twin is known as Predictive Maintenance which helps towards proactive management of assets across industries such as manufacturing, energy and aviation. Digital twins can therefore use live data along with data from before to predict future equipment or asset failures. By keeping an eye on the item's functionality, they may identify degradation and oversee any required repairs. In the end, this preventive approach improves operational efficiency by preventing unnecessary defects and delays. Digital twin-powered predictive maintenance significantly improves asset reliability and reduces costs in the manufacturing, energy, and aviation industries, indicating this significant change (Mengnan Liu, 2020).

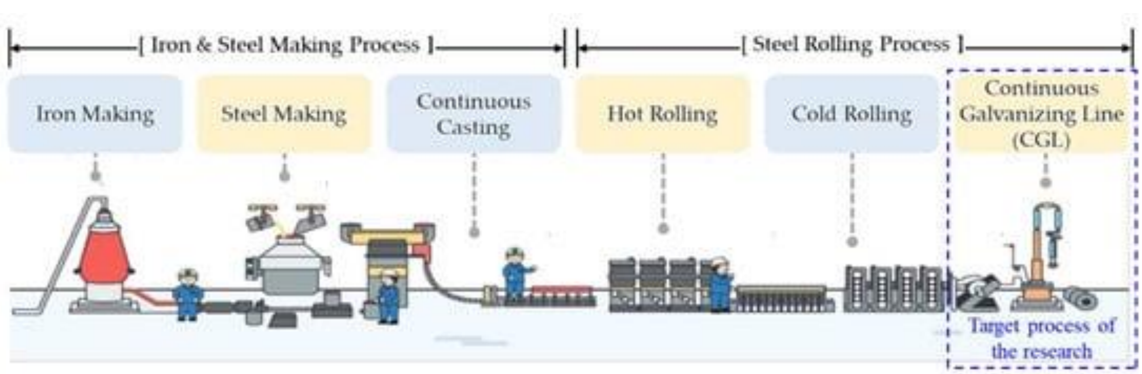

Figure 13: Predictive maintenance in industry (Source: Jin-Seong Choi 2023)

3. **Resource Optimization**

Resource optimisation is one of Digital Twins' key benefits, and it applies to many industries, including manufacturing, energy, and shipping. Modelling and simulating different scenarios with these digital copies helps define resource allocation best practices. Through constant examination and change of resource allocation, digital twins help decrease waste and promote sustainability. Studies have shown this optimisation potential works in several industries. It can improve resource management and environmental responsibility (Matteo Perno, 2022).

4. **Enhanced Decision Making**

One benefit of digital twins is improved decision-making, changing how CEOs handle complex industries like urban planning. Virtual representations of physical systems provide crucial insights for decision-makers. Executives have the ability to test scenarios and assess risks thanks to Digital Twins, which helps them make educated decisions, streamline operations, and avoid mistakes. This is especially useful in sophisticated urban planning, as digital twins help construct smarter, more sustainable cities. While digitally simulating the urban environment, decision-makers can assess risks, model scenarios, and implement data-driven policies that promote adaptation, sustainability, and efficiency (Brintrup & Calinescu, 2022).

Limitations and Challenges

Digital twins have many drawbacks. Data security and privacy in these systems are vital because unauthorised access or fraud can have serious implications. Digital twins must interact with legacy systems and technology, making integration difficult. Scalability is another concern because these systems must manage growing data volumes without slowing down. Large investment costs for sensors, gear, software, and trained staff may further hinder adoption. These challenges must be overcome for digital twins to succeed across industries.

1. **Privacy and Data Security**

When putting Digital Twins into practice, privacy and data security are crucial issues. These systems depend on enormous volumes of data, which often contains private data. This data must be protected against misuse, illegal access, and criminal activity. Data encryption, access controls, and adherence to pertinent data protection regulations (such as the GDPR) are essential. Ensuring that the virtual representation precisely represents the physical system requires maintaining data integrity. Organizations must invest in strong cybersecurity laws, such as safe data transmission and retention protocols, to deal with this concern (Bhuiyan, 2021).

2. **Scaling Problems**

Scalability becomes a major difficulty as systems get more complicated. In order to retain responsiveness and performance, digital twins must be able to handle increased numbers of linked devices, complicated procedures, and volumes of data. System time and decreased efficiency might result from scalability problems. In order to overcome this difficulty, scalable Digital Twins must be created, utilizing edge and cloud computing technologies to manage greater datasets and more intricate simulations (Diego M. Botín-Sanabria, 2022).

3. **Cost-related factors**

Digital twin expansion and maintenance can require lots of financial commitment. Sensors, hardware, software, trained labour, and continuing maintenance are all included in the price. Businesses need to balance these costs with the anticipated advantages in productivity, decreased idle time, and better decision-making. Adoption may be hampered by financial concerns, particularly for smaller businesses. Organizations should investigate cost-effective options and carry out an extensive cost-benefit analysis in order to handle this difficulty (Sharma et al., 2022).

1.6 Operational Excellence with Digital Twins

By using current technology to boost operational performance, operational excellence with digital twins is a business strategy innovation. Digital versions of physical systems enable monitoring and control accuracy. Integrated digital twins into operational procedures enable predictive maintenance, which saves maintenance costs and interruptions. Wide-ranging information and insights help decision-makers make faster, more productive judgements. Modelling and simulation with digital twins enable a continuous improvement cycle that keeps operations resilient and adaptive. A shared digital representation allows teams to collaborate and optimise operations in a culture of continuous improvement, resulting in a new era of operational efficiency.

Effects of Digital Twins on operational excellence

Operational excellence in a variety of businesses is greatly impacted by digital twins, which have become an innovative technology. Significant effects are observed in multiple important areas of operational performance when utilizing these digital copies of real-world resources, procedures, or systems. One of the key effects of digital twins is improved operations productivity. A digital duplicate of a company's tangible assets can provide real-time insights into its operations. Process optimisation, resource allocation, and predictive maintenance are possible. This pre-emptive approach reduces downtime and operating disruptions, improving efficiency.

Figure 14: Digital line of sight (Source: Sharada Prahladrao 2023)

Another consideration is using digital twins to improve product quality. These digital models help test and regenerate product designs during production. Simulations can help companies fix design issues and improve product features, improving quality. This ongoing process reduces issues, improves client happiness, and produces superior products.

Additionally, in today's sustainable world, digital twins assist sustainable practices, which are crucial to operational effectiveness. Training and environmental impact assessment can help people lower their carbon footprint by making data-driven decisions. This encompasses optimising energy consumption, waste reduction, and logistics system environmental friendliness. Business operations can be integrated with environmental responsibility using digital twins.

With the help of digital twins, operational excellence can be achieved. They improve product quality through design optimisation, reduce environmental impact for sustainability, and boost operational efficiency with predictive maintenance and real-time data. Together, these benefits help enterprises make more environmentally friendly products, cut costs, and improve techniques (Qinglin Qi, 2021).

1. **Improved Operational Efficiency**

A digital twin is a technology that allows businesses to have a digital representation of their actual assets, systems, or procedures. Increased operating efficiency is one of this technology's primary benefits Organizations are able to track and regulate their operations because of this digital representation, which has various effective advantages

Most importantly, digital twins provide actual timely insight into real assets and processes in action. Using data gathered from sensors, the IoT devices and other resources, such an organisation may be able to continuously track the condition and utilization of these assets. Predictive maintenance is made feasible as a result, enabling potential errors to be found and fixed before they result in delays or other difficulties. For example, digital twins in manufacturing may help to figure out when equipment needs maintenance, minimizing excessive interruptions in production.

Digital twins provide performance evaluation and improvement. Comparing digital asset activities allows organisations to examine different contexts and settings. This technique optimises operations, improving efficiency and the economy. Digital twins can optimise energy production and distribution systems, reducing costs and energy loss.

Digital twins help people make better decisions by providing a complete understanding of machinery and equipment. This lets firms manage resources, make data-driven decisions, and optimise operations (Ebni et al., 2023).

2. **Enhanced Product Quality**

One of the primary outcomes of Digital Twins, a technique that generates digital copies of real-world systems or things, is improved quality of the product. This effect has a major impact on production and product development in lots of industries.

It is possible that using digital twins, organizations can verify and reproduce the corresponding models in the digital environment without the physical manufacturing process. When carrying out this digital testing and prototyping procedure, it is possible to get to know design problems and improvement possibilities. Product development consequently turns into a more data-driven and dynamic approach. To guarantee the greatest safety standards, for instance, manufacturers can assess several design variations and perform crash events.

Organizations may manufacture goods that not only satisfy but sometimes exceeds quality requirements by improving and optimizing their product designs in the digital age. The experiments help in the prevention of design errors, limitations, and risks that could result in product recalls or quality problems. Consequently, companies are able to provide consumers with items of higher quality, which increases consumer pleasure and loyalty.

Moreover, digital twins make it simpler for cross-functional teams to collaborate and share a single digital product design. This cooperative strategy promotes improved communication and a deeper comprehension of the product design, guaranteeing that every factor from engineering to manufacturing to customer requirements is taken into account (Mohd Javaid, 2023).

3. **Sustainable Practices**

Sustainable practices are essential to operational excellence because they promote efficient and ecologically conscious corporate operations. One of the key practices that has a significant impact on operational excellence is energy efficiency. Businesses can cut their energy use and related expenses significantly by implementing energy-efficient equipment and procedures. This helps to save money and supports the objectives of environmental sustainability. Achieving operational excellence requires the adoption of energy-efficient techniques because it has been shown to improve operational efficiency and lower greenhouse gas emissions.

Operating excellence is sustainable waste reduction practice. Businesses can reduce waste and increase operational efficiency through recycling, material reuse, and production process optimisation. Lean manufacturing, productivity, and environmental impact are improved by reducing waste. Waste reduction is a key practice for organisations seeking excellence since research shows it boosts operational efficiency.

Sustainable supply chain management is essential for companies pursuing operational excellence. By adopting eco-friendly practices into their supply chain, companies can save money and increase sustainability. Implementing sustainable supply chain excellence principles improves operational performance, customer happiness, and financial gains.

Additionally, operational excellence is enhanced via waste reduction, energy efficiency, and sustainable supply chain management. By using these strategies, companies may lower expenses, enhance the environment, and ensure long-term profitability and market competitiveness (Andrea Chiarini et al., 2020).

KPIs, or Key Performance Indicators for Excellence

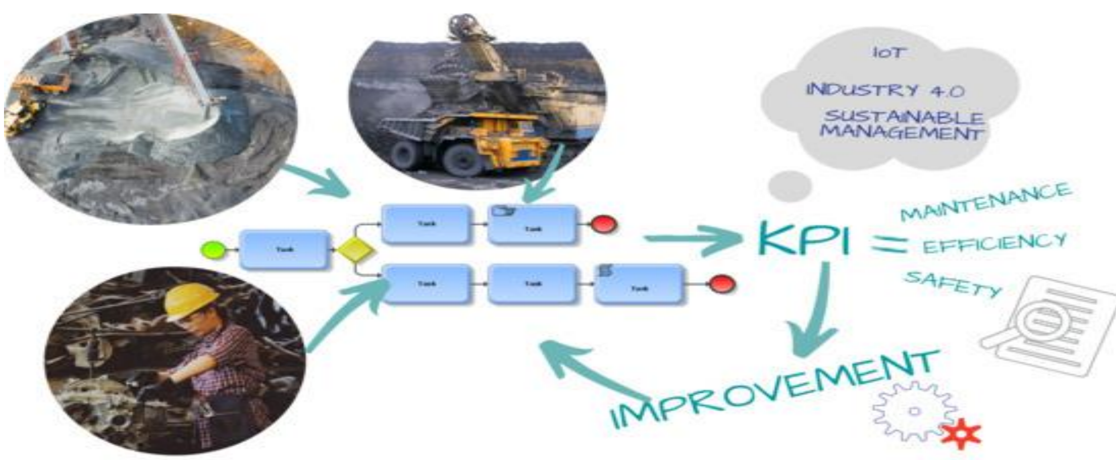

Figure 15: Key features of digital twins (*Source: Paulina Gackowiec 2020)*

The performance and success of companies in a variety of industries are measured and analysed using Key Performance Indicators (KPIs), which are important measurements. They help in evaluating effectiveness, efficiency, and general excellence by offering insightful information on key aspects of an organization's operations. The context of this, a number of research have concentrated on determining and ranking KPIs to promote operational excellence across various industries.

- **Sustainability in the Industry of Leather Products**

In order to determine and evaluate KPIs for operational excellence with an emphasis on sustainability, the leather products sector of an emerging economy. The research study evaluated and classified KPIs relevant to promoting operational excellence in the supply chain by looking through the body of scientific material that has already been published and consulting with experts. The results underlined how crucial KPIs associated with "Management" are to operational excellence from the perspective of sustainability. This demonstrates how operational excellence initiatives are integrating sustainability, which is becoming increasingly important (Oluwaseyi Omoloso, 2021).

- **The Role of Business Excellence During Financial crises**

In their study, Garrido-Moreno, Martín-Rojas and García-Morales (2024) investigated how companies may take advantage of economic crises as a chance to achieve excellence in business. In order to overcome economic issues and improve stakeholder and customer satisfaction, the study emphasized the importance of strengthening strategic planning. It emphasized how crucial it is to put into practice practical business ideas like "Total Quality Management" (TQM), Six Sigma, and Lean manufacturing processes in order to achieve business excellence in times of economic crisis. The main conclusions were improved personnel and management performance, cost savings, process improvement, and quality sustainability.

- **Optimization of Production Processes:**

The optimization of production processes' effectiveness is an important aim for manufacturing firms, as highlighted by (Rut & Wołczański, 2017). The importance of selecting appropriate KPIs and how they relate to one another to promote progress is the main topic of the study. The necessity of precise data from the whole manufacturing system also came to light. It was explained in the article how actual data from IT and production systems might be reliably delivered to a "Web-Based Enterprise Management" (WBEM) server. This is important information for KPI evaluation. Process optimization could be approached entirety due to this integration, which also included information models for KPIs and business process models.

- **Linking Lean Six Sigma with Industry 4.0**

Jaime Macias-Aguayo (2020) investigated how Lean Six Sigma (LSS) concepts and methodologies could be used with Industry 4.0 technology. The study sought to create a new framework for operational excellence through direct observation and the grounded theory technique. It was discovered that although LSS needs both vertical and horizontal integration, it can offer a framework for successful Industry 4.0 application outputs. Reaching Autonomous Process Synchronization, which entails total process automation, is the ultimate objective of horizontal integration. To successfully handle the data gathered from offices and production processes, new analytics are also required.

- **Common KPIs for Manufacturers**

KPIs relevant to a broad spectrum of manufacturers were discovered in (Li Zhu, 2017). Operational performance factors, such as cost, time, quality, and flexibility, were the main focus of the examination. The most widely used KPIs in the literature were found by a thorough examination of 180 publications. Then, using a standardized framework, researchers created eleven key performance indicators to assess a business's entire operations. Organizations can optimize and continuously improve by comparing their operations with meaning when a standard set of KPIs is used.

- **Lean Manufacturing Performance Measurement System**

The "Performance Measurement System" (PMS) was the context of lean manufacturing. The PMS is represented as a multi-level hierarchical tree of KPIs that offers solutions at the tactical, strategic, and operational levels. This methodical methodology assists in the definition and assessment of KPIs that facilitate decision-making. This research also demonstrated the importance of KPIs in the context of Industry 4.0, emphasizing how crucial they are for controlling and evaluating the use of innovative practices and technology.

In summary, KPIs are essential for attaining operational excellence in a variety of operational situations and industries. These studies show that businesses can enhance performance, sustainability, and overall excellence by finding, prioritizing, and using KPIs efficiently. Organizations may better adapt to changing conditions and thrive in their respective areas by integrating KPIs with evolving technology, process improvement, and strategic planning (Albzeirat, 2018).

Significance of Digital twin for operational excellence

In a variety of industries, the usage of digital twins has grown in significance for attaining operational excellence. A digital copy that offers a dynamic, data-driven depiction of an actual system, process, or asset is called a digital twin. In other words, this technology helps companies track, analyse, and improve operations. In many aspects, digital twins are important for operational excellence.

Digital twins are mostly used for real-time asset and process monitoring and control. They gather information from IoT devices and real-world sensors to give real-time insight into these entities' functioning. With the aid of this real-time insight, businesses can react quickly to issues, decreasing downtime and improving operational performance.

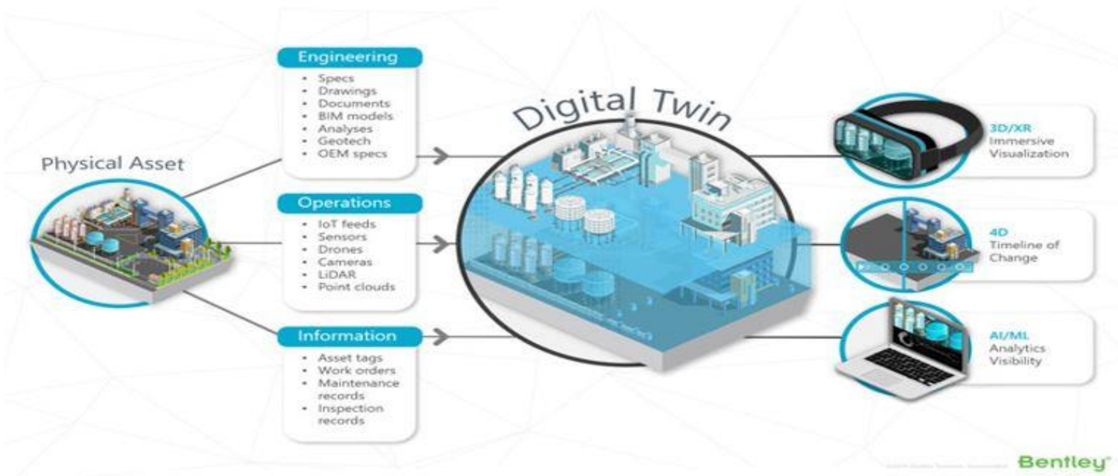

Figure 16: Digital twin interactions technology (Source: Sharada Prahladrao 2023)

Predictive maintenance is crucial to digital twins. Organisations can predict machinery failure using previous and present data. This feature ensures precise maintenance at the right time, reduces unscheduled downtime, and maximises resource utilisation.

Simulation and modelling with digital twins can optimise workflows, resources, and processes. Building virtual representations of activities helps organisations uncover inefficiencies, simulate scenarios, and streamline procedures. Higher productivity, cost savings, and operational efficiency ensue.

Digital twins also enhance use of resources Digital Twins in Construction also enhance use of resources. In order to reduce the expenses and increase the outcomes, effectively the use of resources and people, materials and energy should be maximized. Resource optimization is crucial in industries that are faced with a lot of constraints of resources.

Digital twins reduce operational risk by recognising and assessing risks. Scenario modelling and analysis help organisations make informed decisions to reduce risks. The method boosts operational reliability and stability.

Digital twins are essential for situations when physical access is risky or restricted. This is especially true for remote monitoring and management. Businesses no longer need employees to be present on site because they can remotely manage and keep an eye on assets and processes. For companies which work in hard or remote locations, this is invaluable.

Data is at the core of digital twins. At every level of a company, they produce enormous volumes of data that can be examined and used to make well-informed decisions. The utilization of data to guide decisions guarantees that decisions are founded on up-to-date, precise information, which improves operational excellence (Carvalho et al., 2019).

Contribution to operational excellence

The operational excellence circumstances are being completely transformed by digital twins, which offer several kinds of benefits that have a significant impact on productivity, judgment, and organizational success. Integrating digital twins—virtual representations of real systems and processes—into operational strategy enables the achievement and maintenance of operational excellence. There are several benefits to this connection.

Among the specific advantages of using digital twins, there is the fact that an organization can improve its operational efficiency. Digital twins make it possible for organisations to have real time virtual models of their tangible resources and activities to be able to control them effectively. For industries like manufacturing, where even little variations in the process can significantly affect the output's quality, this precision is essential. By using digital twins, companies can identify and fix issues fast, ensuring that operations run smoothly.

Another important way that digital twins contribute to operational excellence is through predictive maintenance. Conventional maintenance procedures usually involve planned procedures or reactive fixes for malfunctioning equipment. On the other hand, because digital twins continuously track asset performance in real time, they allow for a proactive strategy. Organizations are able to accurately schedule operations as necessary by predicting when maintenance is needed through the analysis of data supplied by digital twins. This increases operational efficiency by reducing maintenance costs overall, extending the life of assets, and reducing time (Mounia Achouch, Mariya Dimitrova, 2022).

Digital twins have an important impact on the processes involved in making decisions. Digital twins offer many kinds of data and insights that support efficient and well-informed decision-making, which is critical for businesses to succeed. Decision-makers have access to a clear digital picture of their business, which enables them to evaluate results, spot patterns, and make the correct choices. The ability to access real-time data is especially helpful in industries that are dynamic and where making immediate adjustments to strategy can mean the difference between success and failure.

Doing operational work proficiently is not an end-point but a continuous process. Digital twins hugely contribute to this feature as they encourage the establishment of the continuous improvement culture. Addressable ability to present and predict various scenarios of an organization's functioning with the help of its digital twin results in experimentation and optimization of corresponding processes. Thus, the operations can do iterations in analysis and modifications to meet market, internal, and external changes. This agility is very important to those organizations that wish to influence the dynamics of the market plan.

Digital twins are critical to departmental integration within an organization for improved operations. The digital representation of systems, assets, and procedures can be used to flatten organisations and enhance teaming. Therefore, integrated collaboration enhances information sharing within the firm hence increasing coordination, communication, and productivity.

Manufacturing digital twins advance the level of performance in production lines by optimizing them. When introducing a digital model of a production process in an organisation, it becomes easier to identify problems, enhance the use of resources and generalize operations. That benefits product quality and production line work. Due to the possibilities of testing variety of scenarios of production in the digital environment, firms are capable to optimise their procedures before using them in practice.

Digital twins enhance energy industry activities through the optimisation of intricate structures such as power plants. The production of these digital copies aids in energy management, effective machinery monitoring, and the prediction of equipment breakdown. Because digital twins offer information on wind parameters and turbine response, wind farm operators may modify their settings. Management of assets before an anticipated occurrence improves the buoyancy of energy systems' reliability, the time exposed to failure, and the costs accrued in maintaining the systems.

Digital twins increase supply chain logistics, a key aspect of operational excellence in many businesses. Businesses can monitor and optimise commodity movement along the supply chain by using these virtual representations. Businesses can make data-driven choices that increase productivity, cut costs, and please consumers by using digital twins, which offer real-time insight across the supply chain from inventory management to transportation logistics.

In the healthcare industry, digital twins are critical to both operational effectiveness and patient care. Healthcare professionals can customise therapies to each patient's physiological characteristics by creating digital twins for each patient. Personalisation improves medical operations by minimising negative reactions and enhancing patient outcomes. Before treating patients, digital twins let doctors practise procedures in the virtual world (Sun et al., 2023).

Digital twins contribute to operational excellence in the real estate and construction industries by enhancing facility operations and project management. Construction sites and buildings can be digitally replicated, giving stakeholders the ability to track developments, spot any problems, and streamline the building process. Digital twins offer a thorough understanding of the building systems, which is useful for facility management as it enables predictive maintenance, energy efficiency, and generally effective facility operations.

Utilizing digital twins contributes to agriculture—which can be seen as the backbone of economies—achieve operational excellence in agricultural practices. Farmers can track the condition of crops, adjust irrigation, and effectively manage resources by building digital twins of their agricultural fields. By reducing resource waste and promoting sustainable farming methods, this precision agriculture approach increases crop yields (Nikolaos Peladarinos, 2023).

The real-time SST technology and components that are the enablers to conceptual, methodological, and practical digital twin for operational excellence include sensor networks; internet of things (IoT) devices; cloud; big data analytics; AI and ML. Cloud computing is a powerful technology that can provide enough resources to process data amounts required by big data concept, at the same time IoT and sensor networks are collecting real time data from physical properties. Whereas big data processing finds out meaningful information from the accumulated data, AI and machine learning give the predictive ability, outlier identification, and optimization.

1.7 Digital Twins for Operational Excellence: Integration with Emerging Technologies

In rapidly evolving technological environment, integrating emerging technologies has become essential to attaining operational excellence across various kinds of the companies. Digital twins, edge computing, block chain, AI, and ML have a lot of potential together. This convergence allows for fundamental changes to operational procedures, enabling new levels of efficacy, openness, and innovation.

Machine Learning and Artificial Intelligence in Digital Twins

- **Effective use of digital twins**

- **AI and ML are essential:** An AI system employs the data held in digital twin to predict the defective digital equipment with the help of predictive maintenance. Because of timeliness and cost saving, preventive maintenance can be done.
- **Optimizing performance:** On the basis of digital twins and machine learning algorithms, it is possible to capture prior data and change operational settings. This enhances the efficiency of resources in the business organizations.
- **Anomaly Detection:** AI identifies anomalies of the activity of the digital twins. This competence is crucial in the early sensing of faults, repair, and minimisation of disruption expenses.
- **Systems for Decision Support:** Combing from the digital twin, AI enhances the quality of the decision that made as the data which used for the decision making. Besides, it is useful for managing risks and their correlation to optimisation of the process.

Real-time data processing and edge computing

Digital twins and edge computing combine to meet the demand for real-time data processing.

- **Reduced Latency:** That is why edge computing eliminates latency and brings computer resources closer to the physical object to process real-time data in digital twins. This is imperative for applications whereby low latency is critical for instance self-driving cars and manufacturing processes.
- **Bandwidth optimization:** By processing data locally at the edge, less data must be sent to centralised servers. This reduces the demand for network infrastructure while optimising bandwidth.
- **Enhanced Security:** By processing sensitive data locally, edge computing helps to improve security. By doing this, the danger of sending sensitive data via networks is reduced, allaying worries about cyberattacks (Teng et al., 2021).

Blockchain Technology to Promote Transparency and Trust

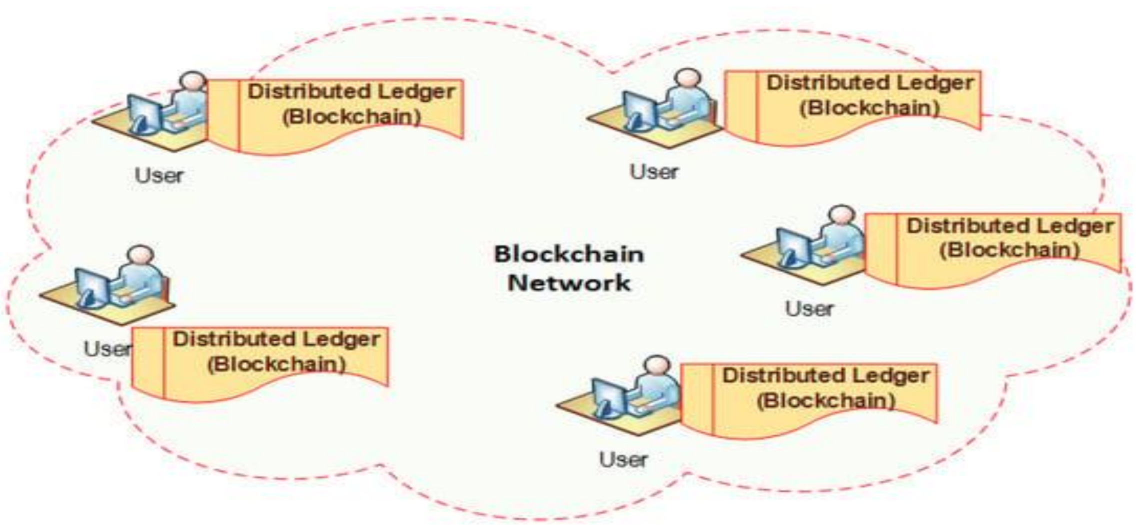

Figure 17: Network of blockchain (Source: Danda B. Rawat 2021)

Digital twins are made more transparent and secure by blockchain technology:

- **Immutable Record-Keeping:** Blockchain ensures digital twin data is safe and unchangeable. Every transaction that is registered on the blockchain generates an unchangeable record, which increases the information's credibility.

  Supply Chain Monitoring Blockchain and digital twins work together to enable end-to-end traceability in sectors like manufacturing and logistics. This integration reduces the risk of fraud and improves accountability by ensuring that every stage of a product's lifetime is securely documented.

- **Automating with Smart Contracts:** The smart contract feature of blockchain automates procedures according to preset criteria. Smart contracts simplify operational operations in the context of digital twins by automatically initiating transactions or actions (Asif Akram, 2018).

Integrating to Achieve Operational Excellence

Digital twins, edge computing, AI, ML, and blockchain all work together seamlessly to build a potent ecosystem that facilitates operational excellence:

- **Effective Resource Management:** AI and ML incorporated digital twins most efficiently achieve the optimal use of resources and distribution, thus cutting down waste and increasing the efficiency.
- **Proactive Issue Resolution:** Thus, using the real-time edge computing, the organizations will be in a position to support the detection of the abnormalities early enough hence closing out any probable disruption elements and issues with a view of being in a position to handle them in a proactive manner.
- **Increased Compliance and Trust:** Blockchain ensures data security and increases its credibility to increase stakeholder’s confidence. This is particularly true for

organizations whose industries have Compliance needs and requirements strictly enforced.

- **Innovation and Continuous Improvement:** The legal basis for innovation and gradual improvement is based on the results obtained from analytics of data in a Digital Twin using AI. Many business processes can be enhanced with the help of analysis based on the data collected.

Edge computing, blockchain, AI, ML, and digital twins can improve operational excellence. This convergence optimises procedures and resource use and fosters resilience and innovation in a changing business environment. These technologies place companies at the top of operational effectiveness and competitiveness, allowing them to grow and succeed (Ezz El-Din Hemdan, 2023).

1.8 Research Problem

In today's highly dynamic and competitive industrial landscape, engineering and manufacturing companies face mounting challenges that threaten their operational efficiency and profitability. These challenges include rising customer expectations for personalized products (Felix, 2015), stringent environmental regulations (Hou et al., 2023), and intensifying global competition (X. Huang, 2023). To navigate these complexities, organizations must embrace innovative technologies that drive operational excellence and optimize resource utilization.

In this rapidly dynamic and competitive industrial environment, engineering and manufacturing companies are in essence under siege by challenges to their operational efficiency and profitability. The challenges of rising customer expectations for personalized products Felix, (2015), stringent environmental regulations Hou *et al.*, (2023), and intensified global competition Huang, (2023) have to be faced. To overcome these complexities, organizations need to adopt the most innovative technologies to enhance the operational excellence and maximise the usage of resources.

These objectives can be accomplished with the help of Digital twin (DT) technology. DTs create virtual replicas of physical assets, processes, and systems allowing for real time monitoring, predictive analytics and process optimization. Nevertheless, despite its promise, the DT implementation has not been fully realized in terms of how to completely utilize DTs to enhance product quality, reduce costs, and increase operational efficiency. Besides the high cost of DT adoption, many organizations cannot justify its economic viability, and measure ROI or prove its impact on KPIs. Also, there are no best practices for optimizing production processes and for integration of DTs with the Engineering, Procurement, and Construction (EPC) principles.

In particular, this research attempts to address these gaps by systematically investigating when and how DT adoption can translate into significant economic benefits; what the ramifications of this substitution will be on the operational KPIs; and how the cost reduction and process improvement can be achieved. This study will identify how DTs help achieve operational efficiency and quality by examining how DTs contribute in achieving operational efficiency and quality.

1.9 Purpose of Research

This paper addresses the research question on how engineering and manufacturing organisations can enhance operational performance through effective utilisation of Digital Twins (DTs). The aim is to shed some light on the implementation of DT concrete operation impact, its financial feasibility, and the ways for optimization.

Therefore, the study objective is to examine the cost – effectiveness of leveraging digital twins in engineering and manufacturing disciplines. This includes establishing of some quantitative values and grasp of revenues and possible returns on investment for the various businesses in the economy. The study focuses on the financial aspects to enable the evaluation of the economic feasibility of DT integration by organizations.

The second objective aims at assessing the effect of digital twins on operations excellence. This method entails the analysis of many KPIs to assess the implementation of DT. To organisations that are interested in attaining operational capabilities, it is critical to consider on how DTs impact on operation efficiency, resource consumption, and output.

Thus, the third objective of the study is to optimize and reduce cost of manufacturing processes. Out of this paper, the researcher seeks to understand on how to employ DTs to improve engineering and manufacturing to improve productivity while reducing costs. This segment focuses on the concrete problem that companies experience when applying DTs for performance enhancement.

The fourth use of the project is to identify the efficiency gains of the operational Digital Twin technology. This involves learning on the way in which DT helps in managing responsiveness, operational scenario dynamism, as well as flexibility. An understanding of how to leverage on the DTs for enhancement of productivity is crucial to the companies that are trying to remain relevant in dynamic economies.

The paper also touches on the following topics: improvement of quality and standardisation of products by use of DTs. Also, the study will highlight tools and techniques in which digital twins are applied to track and improve product quality to assist producers in providing quality goods.

Finally, the study looks at integration of the digital twin technology with the EPC concepts. This section focuses on the possibility of enhancing the project management processes through the implementation of DTs for higher efficiency and outcomes.

1.10 Significance of the Study

This important study describes how Digital Twins (DTs) can enhance manufacturing and engineering operation improvement. Some of the challenges that sectors experience include; producing customized products, stringent environmental standards, and the rising global competition. Success in the long term depends to a large extent on doing this complexity well. Since there is minimal literature on how to maximize on the outcomes of DTs in order to increase productivity, reduce costs within the organization and the whole efficiency of the organization, the following objectives are proposed.

In this respect, the purpose of the study is to assess the possible return on investment (ROI) as well as cost implication of businesses adopting the use of DT. This will aid decision-makers. Thus, to gauge how DTs drive operational improvements, one needs to consider how they impact measures of productivity. The research offers practical advice for business executives on how to streamline manufacturing procedures, reduce costs, and increase productivity.

Due to the growing emphasis on manufacturing quality, DT methods and instruments to improve product quality and uniformity are important. Digital twin technology with Engineering, Procurement, and Construction (EPC) concepts may improve project efficiency and give a comprehensive approach to operational excellence.

Many stakeholders, particularly in the engineering and manufacturing industries, are expected to benefit from the research's findings. DTs can reduce costs, boost operational efficiency, and make better goods for big and small businesses. DT technology may help engineering firms optimise project management.

The research contributes to the greater scholarly and industry discussion on DTs by providing practical applications specific to the engineering and manufacturing industries.

As the industrial environment develops, practical and sector-specific insights are increasingly important for informed decision-making.

1.11 Research Purpose and Questions

The primary aim of this study is to investigate and demonstrate how Digital Twins (DTs) can be effectively leveraged to enhance operational excellence in the engineering and manufacturing sectors. Particularly, the study has the following research questions:

1. What are the distinct economic advantages of applying digital twin technology across different industries, and how can the return on investment be calculated and evaluated?
2. What KPIs are most important for evaluating how digital twins affect operational excellence, and how do they change depending on the operational environment and industry?
3. What are the most effective methods and strategies for optimizing production processes and reducing costs through the use of digital twin technology in manufacturing and industrial settings?
4. What are the approaches that contribute to increasing the overall operational efficiency?
5. What are the most effective tools and techniques in order to leverage digital twin for improving product quality and consistency?
6. How can digital twin technology be integrated with EPC principles to enhance project efficiency?

The result of this study will be valuable for a wide range of potential users. The engineering and manufacturing sectors, in particular, stand to benefit greatly from the information given. A better grasp of how DTs can result in higher product quality, lower costs, and more operational efficiency would help manufacturers of all sizes. Engineering organisations will find assistance on how to optimise their project management processes through the incorporation of DT technology.

1.12 Summary

A clear uptick in the practical application of digital twin technology has been observed over the last few years, a phenomenon that has not passed unnoticed by either researchers or managers. Parallelly, with the IoT, IIOT, and AI evolving, people came up with the idea of digital twins. This is because while much research has focused on using digital twins in the manufacturing industry, there is limited information on the use of digital twins in smart cities and healthcare even though digital twins are widely adopted in many other fields.

Digital twins are avatars to real-life processes, methods and or objects that can offer actual time info to help in decisioning. It is a phenomenon composed of data merged from quite a few sources such as sensors and Internet of Things devices and AI for computation and estimation. This integration can be associated with Digital Twin model whose implementation has lately become widespread.

The manufacturing sector's many articles show its importance by research. These articles discuss Digital Twins in manufacturing, focusing on machine health and predictive maintenance. Predictive maintenance helps businesses enhance productivity and reduce downtime by enabling early repairs or replacements.

Smart city traffic management systems and urban development are increasingly using Digital Twins, according to the paper. Smart cities may model and enhance utility, infrastructure, and transportation flow via digital twins. The subject of study is increasing and could affect urban planning and administration.

It emphasises the need to broaden Digital Twin research beyond manufacturing. Digital Twins are being developed by researchers to meet specific purposes. Chances and challenges vary by sector.

CHAPTER II:

LITERATURE REVIEW

2.1 Economic Benefits of Digital Twins

According to Wagner et al. (2019), In several areas of the product engineering process, digital twins present excellent prospects. However, the methods used today to take use of digital twins are limited to particular fields of study. However, since they make it possible to produce goods with competitively high performance, subsequent product generations are anticipated to be produced based on the application of DTMs within the product creation and production sectors. This essay considers major issues and potential in the context of execution of digital twins and Industry 4.0 for linking product design and production. In this sense, methods for integrating digital twins with other domains create new opportunities for production integration and tolerance allocation. In this way, the producer is able to attain the most economical and technically efficient product parameters. Furthermore, Industry 4.0's connectivity expands the possibilities and makes it possible to assess different strategies for production planning and control. High performance operations are provided by organisational strategies, product functions with technologically impossible standards, and production control tactics (e.g., order dispatching). Early estimates can be made using simulations that combine an integrated digital product twin and digital production twin, even before the product is fully ramped up. Techniques like digital twins can only be applied uniformly throughout the entire product development cycle, requiring the configurations of production planners and product designers. This difficulty is discussed in this article.

The following research, Preut, Kopka and Clausen (2021) evaluated for materials and goods to be circulated, accurate information is essential. It has an impact on how successfully activities like reconditioning and the related supply chain management are carried out both economically and environmentally. Concepts related to digitization, like digital twins, allow pertinent data to be decentralised and made available to the appropriate actor at the appropriate moment. Digital twins are predicted to be significant players in the future and to be able to help successfully implement circular economy plans among other things. Nonetheless, the investigation and application of digital twins concerning circular economy items and supply networks are still in their early stages and require a shared lexicon. The potential benefits of digital twins for managing circular supply chains and increasing product circularity are discussed in this article. This explains how a meaning for the term "digital twin" was created and confirmed. A stakeholder analysis that concentrates on the procedures of the individual stakeholders provides a summary of the information requirements and opportunities for digital twin circular supply chains. The study comes to the conclusion that digital twins can help circular supply chains, but more research and development is still required, especially for use cases and product-specific applications of the idea.

The research, Pylianidis, Osinga and Athanasiadis (2021) was to identified a rising number of sectors are adopting digital twins, which are changing them and opening up new opportunities. Digital twins help manage complicated systems and offer unprecedented levels of control over physical objects through the integration of many technologies. It's still unclear whether the agriculture industry is attempting to integrate digital twins into its daily operations, even with the latest technical breakthroughs. The author of this work examines the value addition of digital twins for agriculture using a mixed-methods approach. The author looks at how widely digital twins are being used in agriculture, explain the idea and its advantages, and offer an application-based roadmap for a wider adoption. The author presents an assessment of the research on digital twins in agriculture from 2017 to 2020. The author compares the 28 use cases she found to use cases from other academic disciplines. To estimate the extent of digital twin usage in agriculture, the author analyses the service types, technical readiness levels, and declared benefits. Analyzing the applications of digital twins discussed in the agriculture and numerous other industries, the author identifies the characteristics of digital twins that can benefit the agriculture sector. Building on this, the author provides memorable examples of how these concepts of the digital twin may be expanded further in the agricultural space; examples are derived from the use of digital twin solutions in other industries. In the study's conclusion, the author outlines the unique characteristics of digital twins for agriculture.

2.2 Cost-Benefit Analysis Framework

The paper, McClenaghan et al. (2023) focused on the relatively new idea of Digital Twins, including making near perfect digital clones of actual items or processes. These replicas are built using a combination of distinct sensors and modelling which entails analytical, numerical and artificial intelligence modeling. This paper is primarily concerned with a significant problem that, apart from the specifics of developing these Digital Twins, there is no systematic approach to classifying the structures of these twins and deriving a definitive net return on investment. The cost-benefit sensitivity analysis is composed of a major part of the research, carried out to investigate the differences between two aspects of the Digital Twin model with two different specialized components used to simulate the position of a thermally sensitive assembly. From the perspective of the present study, this analysis highlights the breakneck pace at which organisations need to understand the financial rational for various components of a Digital Twin model, and how Financial Digital Twin needs to an essential element of this complex solution. The paper also notes that fidelity of Digital Twins can vary, with low to high degree to accommodate various use cases. To make sure these digital twins will deliver real-time data and information, sensors, simulation, and modeling techniques must be integrated into their production assuring efficient performance optimization and enhanced decision-making across the sectors. Moreover, the paper presents a classification of Digital Twin architectures, which is crucial to introducing common practices to the process of Digital Twin creation. Therefore, through a focus on the costs and benefits, the paper stresses the need to conduct specific assessments before using components of the Digital Twin model. They guarantee efficiency in the expenditure on Digital Twins while at the same time making sure that those expenditures are wise. In conclusion, the given paper offers main theoretical and practical contributions that enrich the knowledge about and the practice of Digital Twins. It gives information on the issues and the factors to consider when implementing and using Digital Twins, offers a strong classification of them and underlines the need to consider cost-effectiveness ratios. The industries that are interested in using digital twins to increase performance and efficiency and make decisions may find these contributions useful.

The findings of the study, Buonocore, Yates and Valentini (2022) indicated that it is commonly acknowledged that forest ecosystems are becoming more and more important to human society and the health of the planet. New and integrated methods of monitoring forest ecosystems are made possible by the development of data gathering technologies. This work aims at giving the basis for constructing forest digital twin (FDT) at the main tree and forest state variables. That said, the above sources of data depending on the use cases that a given implementation of the framework provides may be integrated in the management of health of the forest, research to achieve sustainable forest management. Twining individual trees, which uses real-virtual digital sockets to record the biotic and physical state variables of the tree and its surroundings, is a crucial component of the FDT. This makes it possible to get the intended outcomes. When data is gathered at the forest scale from sources like flux towers and remote sensing technologies, a layered approach can be used to interweave the entire forest, including the twinned trees and the associated physiological and physical processes. Therefore, the FDT should launch a distributed ledger that will incorporate blockchain and smart contracts to capture optimal economic benefits from the use of forest ecosystem services. This will in turn enhance the measurement and mitigation of forest risk, increase the flow of capital towards forest sustainability plans and ensure high quality reliability, openness and completeness of data and related transactions.

This research, Kober et al. (2022) Inferred The DT and it's specific implementations, the DM and the DS is a fairly promising concept in the context of SM and Industry 4.0. The number of scientific articles and actual uses of DT has grown considerably after its fundamental technologies, simulation, IoT, CPS, Artificial Intelligence, and big data, started to develop slower. Further from academia, DT is defined as the true-to-life replica for a physical object, emulating all of its characteristics to the maximum. Moreover, the one which the DT is concerned with is capable of changing this physical entity in consonance with virtual changes. Fidelity hence pertains to such parameters and the degree of accuracy and abstraction. Nevertheless, the flows of the high fidelity are questionable in the context of the range of the benefits which are supposed to be gained in practice. Given that there is no structured method in the present literature that aids scholars and practitioners in elucidating the right levels of fidelity, That is why in this article a tentative solution suggested is the Digital Twin Fidelity Requirements Model (DT-FRM). In order to implement it, Design Science Research methodology was used and concepts based on it have been employed. In the first step of the DT-FRM, it is assumed that a clear problem definition is possible – then it continues with the breakdown of the problem into dependent target variables (1), out of which the extent of the problem is derived (2), the independent variables underlying the problem are defined (3), and the fidelity of each variable required is determined (4). Thus, by the usage of DT-FRM users successfully solve their initial problem with no or limited DT implementation and subsequent costs. Evidence exists that it might be necessary for decision making to evaluate the right amount of DT fidelity to achieve the intended benefits and minimize the associated implementation difficulties in manufacturing.

The current study, Caccamo et al. (2022) represented that the fourth industrial revolution is gaining momentum even if it hasn't yet reached its maximum potential. According to a number of studies, a large number of businesses worldwide have started the process of digital transformation, but the majority are still far from reaching full adoption and are therefore locked in what has been referred to as "pilot purgatory," failing to see the full economic potential. Although most people agree that digitalization speeds up and facilitates complete automation in manufacturing, businesses are still finding it difficult to determine how digitalization will affect operational performance metrics and return on investment. Consequently, businesses are hesitant to invest further capital, particularly small and medium-sized businesses (SMEs) that function in high-value, high-mix, low-volume, volatile contexts. Digital twins can be used to show usage scenarios, assess their impact, do away with physical prototypes, expedite development, and enhance quality by combining simulation, data analytics, and behavioural models. They can also help ramp up automation systems. While most advanced organisations are limiting the transformation necessary for sustainable manufacturing, a small number of them are pursuing digital transformation. In order to fulfil the potential of the digital industrial revolution, this study suggests a theoretical method for utilising digital twin technology to provide insights for a practical and cost-effective evaluation of whole automation systems. The ultimate objective is to encourage investments in this manner. Under grant agreement No. 958363 of the European Union's Horizon 2020 research and innovation initiative, the method is being evaluated. This offers a chance to evaluate, through a real-world example, how the different parts of the method are put together, how complex they are, and how much work is involved.

2.3 Impact on Operational Excellence

Key Performance Indicators (KPIs) for Measuring Operational Excellence

Yusupbekov et al. (2021) presents novel approaches and techniques for computer modelling of various industrial asset layers and characteristics. This study considers and describes novel software methods for both developing the model and the software environment that will enable the models to communicate in real-time with an actual industrial plant. Although other categories of “digital twin” models relevant to industrial use cases are also reviewed, the main concern of this research is the “digital twin” models for enhanced efficiency and asset health management. Some basic physical model types, such thermodynamic or first-principle models, are well-known to the scientific community, while other modelling approaches, like fault-symptom or data-driven modelling, are newer and have to do with industrial "digital twins." The study presented in this paper aims to discover the scientific and technological ways in which industrial businesses can achieve unprecedented levels of performance and efficiency, levels that can only be attained through the use of digitally intelligent, real-time infrastructure.

The study, Marmolejo-Saucedo et al. (2020) identified that with the aid of digital twin technology, actual objects or procedures can be digitally recreated to resemble them in behaviour. Analysing its performance or behaviour in specific situations is the goal in order to increase its efficacy. The digital twin idea may be employed to refine the current state, search for past information, and predict future gauges of change of the various segments under analysis. It can be for devices, or bigger and more abstract things such as goods, or entire business ecosystems. Digital twins are revolutionising the operations of supply chain-related businesses by offering a variety of solutions that facilitate data-driven decision making, teamwork, and more reliable business procedures. This essay proposes creating a digital twin for a pharmaceutical corporation case study. Utilising simulators, solvers, and data analysis tools, the technology enables the coupling of several tasks in a crucial interface for the business.

The paper, Psarommatis and May (2023) explored and determined that the utilisation of digital twins (DTs) has been the subject of numerous studies. It is possible to evaluate DT performance, but there is no set way to do so. The performance evaluation tool provided by digital twins is crucial for improving or keeping an eye on any system or process within an organisation. Researchers and practitioners could utilise this technique as a roadmap to help them create more successful digital twins. Their research provides a way to use four key performance indicators (KPIs) (Such as Accuracy of the DT, Accuracy Variance, Response Time, Response time Variance) to statistically calculate the performance of digital twins (DTs). Motivated by these issues, the author offers a systematic way to evaluate the efficiency and adaptability of DTs. In order to evaluate the adaptability of digital twins, the author additionally suggests a novel KPI known as DTflex. In order to show how easy it is for practitioners and designers to compare various DT methodologies, the author assessed DTflex's performance as a KPI. This information could be useful in the future for iteratively improving DTs to make them more efficient. It is expected that decision making about DT performance and techniques will be more beneficial as many sectors' researchers and practitioners will utilize the knowledge and method proposed in this study to apply more effectively for DT solutions and to get more repurposing from already developed DTs.

Comparative Analysis of KPIs Before and After Digital Twin Adoption

The study, Maheshwari et al. (2023) examined that as of now, the shifting concept studied in the Alphabet Theory in the advancement years of Industry 4.0 such as the Digital Twin or DT has brought increased focus among scholars and professionals. Most DT research are theoretical in nature and focused to hypothetical analysis there are very little numbers of studies based on empirical real-life situations. Although being inconsequential in formulating business strategies, DT technologies are popular in performance improvement research in FPCs owing to their abilities to dynamically solve problems. Their research solves the actual challenge faced by the food processing corporation (FPC) by combining DT technology with an implementation case study. Moreover, A thorough examination of the many stages of DT implementation, including strategic mapping and the replication of physical and virtual places, is provided by the suggested DT research methodology. The findings demonstrate how DT improves the machine availability, throughput rate, step ratio, technical efficiency, labour efficiency, and efficacy of the current system. All the variations of the Logic software that has JAVA-capable programming are employed to execute the physical-virtual interface model proposed herein.

In this paper, Papacharalampopoulos et al. (2020), the author writes about the concept of the Digital Twin based on the accumulated KPI obtained from the IoT information regarding underlying causes of the production alerts. In contrast to earlier conventional models, this Digital Twin achieves determinism by using real data that has been freed from noise. The use of linear regression, which evaluates real-time planning performance and searches for potential weaknesses in trend analysis, aids in operational decision-making. A KPI analysis method, which is incorporated in a dashboard, automatically diagnoses the variables that are leading to worse performance through prediction of the threshold values. In other words, this type of a dashboard can act as an abstract form of a DT to help the production managers with improved levels of automated decision-making. Latter work comprises incorporation of the knowledge-based library for identifying actions and application of more advanced statistical characteristics and derivatives. Unlike other methodologies it has the ability to analyse the past production data for future behavior and the identification of detrimental performance influences without training; And the implemented Java-based dashboard stores all data into a database via Online Analytical Processing (OLAP) server for easy configurable management of all Key Performance Indicators KPIs.

The study, Papanagnou (2020) revealed that Prior to this, manufacturing organisations found using digital twin technology to be a significant barrier in terms of shop-floor dynamics and data visibility, which had a significant impact on production scheduling and tracking. By comparing the real performance based on KPIs before and after the DT platform was implemented, this article sought to examine the impact of DT on an assembly line. Through the comparative assessments, it was possible to capture quite major enhancement on the ability of the firm to comprehend relationship between shop-floor data and production performance particularly on throughput levels. Thus, the DT platform allowed for controlling the whole life cycle of a plant with the help of real-time data on the machine temperature levels. Data collected at the shop floor provided the means through which DT platform utilized to forecast production performance, excessive downtime and yield rate thus demonstrating the DT advantages in production. The study established that digital twins improve manufacturing performance through availability of data and best practices analysis. The role of DT platform was most significant where assembly line was involved as was the case with different workstation or with a large range of products. Altogether, the comparative KPIs applied in the case helped to prove the drastic change that digital twin technology brought to manufacturing processes and supported data- and performance-oriented decision making as well as improvement of production.

Best Practices for Enhancing KPIs through Digital Twins

Research findings, Biller B and Biller S (2023) showed that Implementing digital twins involves three key functions consists of three processes: flexible online delivery, real-time synchronization and developing offline models. That step is called 'offline model development,' which seeks to enhance it; it requires using the numbers produced when setting up the digital twin of the factory to benchmark it against the past performances data. Real-Time Synchronization makes sure that the factory and its digital twin synchronise and remain updated by pulling the most recent data for model parameters at certain intervals. Factory Monitoring, Performance prediction, and Optimization is a part of Online Learning. Other closely related technologies are AI/ML, simulation, forecast, optimize, Econometric, Visual analytics, and streaming analytics. Digital twins increase the visibility of the future, can be used for operational decision-making, and for simulations of the best possible outcomes. From this, they can see that, depending on the sorts of input data and models employed, two types of simulations are required for MSP: offline model development and online learning. Some issues that are related to digital twins include how to have more than one twin in a supply chain configuration, how to collect the right data, and how to apply the right kind of analysis. It is worthy to note that the time scale associated with digital twins depends of the frequency of decisions made; whether it is the urgent need for maintenance of critical assets or stock replenishment. Inter-Development learning minimizes development time since the various developments learn from one another; it also enhances staff organizational efficiency by increasing utilization; ultimately, this optimizes the developments in the digital twinning process.

The results of study, Yang, Langley and Andrade (2022) indicated that the important thing here is the metrics that can be classified into KPI-free and KPI-based to optimize Key Performance Indicators (KPIs) using Digital Twins. The metric of the average information using the idea of design entropy is the sole KPI-free metric of the article that does not rely on a fixed design target for the distance between the nominal and Latinized points during the early design stage. This metric comes in handy as design advances to a detailed stage where targets have already been set; the main design standards aimed at deciding either acceptance or rejection are also in place. This interdependence of the metrics guarantees the evaluation of the extent to which the recognized high-value information aligns with the envisaged design throughout the process. Using the moments/moments-of-moments of the underlying QoI distribution, the KPI-free sensitivity usually reveals parameters which become important in the later steps of the analysis. Both the approaches help designers to trend on parameters that will remain constant in near future and which fits into changing KPIs. The dynamic design of an offshore structure can be used as an example where it is crucial to use both measures for improving KPIs, especially in cases of uncertainty. Incorporation of a non-intrusive sensitivity metric that comprises of KPI-free and KPI-based sensitivities maintain high-value data identification container checks whenever uncertain data appear during the design.

The master's thesis, Dhanush and Gopalakrishnan (2021) was It is one segment of the larger pilot study for the EU-supportive industrial project “Twin Goals” at the EIT and Chalmers University of Technology. The purpose of this research was to establish whether using a digital twin might ensure the sustainability of production. Previous studies have demonstrated the possibility for remote industrial process management and monitoring utilising Digital Twins based on Cyber-physical systems (CPS). This is achieved by establishing a two-way information flow between virtual entities and real assets. Through information sharing, this project aims to improve real-time manufacturing process optimisation and raise the production system's sustainability. The investigation was carried out at the Stena Industry Innovation Lab (SII-Lab), Lindholmen, Gothenburg, in a drone manufacturing test facility. The approach employed in this thesis is a combination of triangulation research methodology and banking methodology. In order to determine appropriate Key Performance Indicators (KPIs) for monitoring the economic, ecological, and social elements of sustainability, a literature study was carried out. Both qualitative and quantitative research was done while the model was being built and the analysis was being done. To construct the drone factory's DES model, four scenarios were used: The AS-IS scenario represented the current condition, whereas the base scenario contained a possible "operative digital twin" scenario with a dynamically rebalanced station; an additional product variant was included in the experimental scenario; and a parallel station was involved in the experimental scenario 2. To evaluate the scenarios, experiments were conducted using varying pallet sizes and client expectations. The results of experimental scenario 2 out of the four suggested that Triple Bottom Line (TBL) would gain in the economic and environmental spheres. The operational scenario demonstrated the independence with which the production resources could be employed, guaranteeing that the system's production load was dispersed equally throughout all processing stations. In this scenario, throughput increased and material and energy efficiency improved while lead times, waste, and non-value-adding operations decreased. They may introduce the potential Digital Twin for production sustainability if data are allowed to flow between the assets and this operational environment.

2.4 Optimization of Production Processes and Cost Reduction

Techniques for Process Optimization Using Digital Twins

The author, Tian, Yu and Gu (2024) found that digital twin modelling augments the simulation and prediction setting by explaining associations between physical entities and responsive digital analogues using computers, mathematics, or physical means. Data generated digital twins are useful in the management and decision making involving system behaviour complexity and Variation and these are effective in process improvement while those derived from models use physical laws for reliable improvement based on physical features and limitations. Integrating both can help to extend the use of digital twins for process improvement even more. To develop such models, the objective, application environment, input, and output must be determined first, and further, based on technical aspects, simulation software or programming languages like Arena, Simio, C, C++, Java, or Python are chosen. Digital twin technology allows one to mimic and control equipment or a precise process by building virtual models that are embedded with the system's real-time requisite performance metrics and physical environment. Hence, Because it can improve configuration and safety, increase efficiency and reliability, and reduce operating costs while also improving employee training and technical proficiency based on data from sensors and the use of corresponding digital twins of business processes used to monitor, predict, and optimise operations and the corresponding maintenance strategies, this technology is best suited for the mining industry.

The study, Rührlinger, Stary and Jost (2024) examined an immersive method of offering services in virtual environments based on multiple technologies, including extended reality, is provided by the Metaverse. Its importance to organisations is growing because of its ability to support business arguments. Using digital twin methodologies can support the human-centered development and operational deployment of Metaverse applications in this setting. The article looks at current methods used in this situation. The goal is to be able to assist users and developers in creating and utilising Metaverse applications by using digital twin technologies in a stakeholder-centered and productive manner. The conclusions drawn from the study are based on an examination of existing ideas in terms of their applicability, taking into account the particular needs that come from Metaverse applications. It is not just seen as a representation of the physical world, but also integrates processes that occur only in a digital form. This is predicated on a modified conception of the digital twin. There is a corresponding development and deployment framework available.

The work, Svadkovsky (2024) examined how the elements of Digital Twins affect the business processes of mining organizations in stripping and mining, enrichment, and transportation. Thus, when various possible mining situations are simulated, critical points are defined, and effective decisions are made, several points will be improved due to which productivity and efficiency of the operation will markedly increase. This level of efficiency is advanced by the use of Predictive Maintenance Plans tied to Digital Twins which reduces chances of equipment failures and optimizes the use of the equipment. In terms of technology, Digital Twins can improve the upper area of commercial products after enrichment and the efficiency of the production line of mining equipment. These enhancements are beneficial for the operational efficiency and EBITDA and cash balance growth. An evaluation based on Digital Twins determined the index and transitional important spheres of production. An empirical study revealed that adopters anticipated a lift in their EBITDA by 28 % from Digital Twin implementation; however, the achieved results demonstrated a preferable figure of 21%. Similarly, they expected a 130% hike in free cash at period end; nevertheless, the actual enhancement was 96%. Hence, there is insight into the resemblance of the use of DTs in the improvement of operational efficiency to address challenges that are unique to mining companies.

Cost Reduction Strategies Enabled by Digital Twins

The study examined that Rigby and Christmas (2023) other advantage of Digital Twins is that cost reduction strategies accompanied by Product Lifecycle Models can be monitored through certification and maintenance data all thanks to Digital Twins. This means that, by automating the process of data collection and updates within these models, there will be timely update of information, thus cutting down the costs in terms of manual labor to a certain level. Applying Digital Twins right from the Concept Design phase and updating them from time to time fosters the growth of the models into more sophisticated ones, whereby the possible cost advantages are colossal. Using one hull into which all of the systems are integrated can also provide potential on savings on building multiple twins of a ship for each of the subsystems for example; cost saving factors are however still limited by commercial and Internet Protocol (IP) restrictions. Further, as with any Digital Twin type, the intricacy and benefits presented by different Digital Twin types can assist in finding cheaper approaches to the problem by separating low-complexity systems from comprehensive ones. Finally, no matter what name is given to these concepts, the prime value should be in what operations and designs Digital Twins enable, often how the assets under management increase efficiency, effectiveness of decisions, and reductions of costs.

The study, Caiza and Sanz (2023) examined that A technology known as Digital Twin (DT) has emerged as a result of growing industrial development and digital revolutions, and it has the ability to dissolve the boundary between physical and cyberspace. Through bidirectional data flow, DT, a virtual and dynamic model, is made possible, enabling the creation of high-reliability models that fuse and integrate digital and physical systems for complete integration Smart manufacturing research and business are using this technology more and more. The conducted research, however, fails to offer either a definition or a unified model. To identify the industrial architectures and technologies of the digital twin, the research surveyed the existing literature. In an attempt to implement an augmented reality digital twin, a methodology collecting data about the physical process, constructing a digital environment replicating the physical one, expressing the physical environment, simulating the models applied to the digital environment, and adjusting key parameters of the simulation environment to those of the physical process in real time was employed. However, neither a definition nor a cohesive model are provided by the research that has been done. For the purpose of informing the characterisation of digital twin's industrial architectures and supporting technologies, the research reviewed all available literature. The technique was used to capture information about the physical flow, build the virtual world, make that world available to others, execute simulation models in that world, and update the parameters in that virtual world with reality-time process data to develop an augmented reality digital twin. The system was implemented in the MPS-500 modular manufacturing station, which has industrial sensors and actuators. To create the augmented reality scene, Blender and Vuforia were used in the virtual environment design process. The proposed technique generated and communicated with the virtual environment (monitoring and control) using inexpensive embedded systems and dependable devices (field and control level). Thanks to the Open Platform Communications United Architecture (OPC UA), Ethernet connection and machine-to-machine (M2M) protocols, it became possible for these technologies to work together as a single system, as they encompass the entire automation pyramid. Based upon the results, one may suggest that augmented reality may be employed to visualise the peculiarities of the DT and that the suggested method for adopting it facilitates bidirectional interaction between the physical and digital environments.

Both the realtime and the latency requirements for digital twin are met as these offer bidirectional connections over the Ethernet protocol with a transmission time of about 100 ms which is vital for constructing the virtual worlds and improving applications that helps to integrate real and virtual realities. This technology accomplishes dynamic and timely alteration through mapping and interacting with the virtual world. Real-time integration of process simulation and physical control can enhance production and data management. This makes it possible for simultaneous execution and triggering of activities in the actual equipment.

The principal goal of the study, Waclawek et al. (2023) was Operational Technology (OT) systems must now meet additional requirements as part of the Industry 4.0 concept. These criteria already have information technology (IT) soutions; however, because the two domains are so dissimilar, these solutions are frequently not applicable directly to the OT environment. As a result, they describe the idea of an Industrial Business Process Twin (IBPT), which enables the application of techniques from one world to another through a representation that engages in two-way communication with the other world rather than directly. By serving as a middleman and severing the link between the IT and OT domains, the proposed IBPT organisation makes it possible to integrate IT and OT components from various platforms and manufacturers. Using the gamified Industry 4.0 scenario of playing the game Nine Men's Morris, they use this method to demonstrate the four key design elements of Industry 4.0: such values as information openness, technical assistance, interdependence, and decentralised decision-making. This setting has impact on the direction and formation of agent based artificial intelligence (AI), scientific research and learning. This builds on an earlier information and communication model known as Open Platform Communications Unified Architecture (OPC UA). It also evaluates the IBPT component based on RAMI 4.0 of Reference Architecture Model for Industry 4.0.

2.5 Increasing Overall Operational Efficiency

Approaches to Enhancing Operational Efficiency with Digital Twins

The purpose of this investigation, Ma et al. (2024) was DTs are a massive leap from the previous type of thinking that provides a platform for modeling the said systems with an aim of making changes to the systems in endeavor to model the said systems in the virtual world in order to gain better control of the systems. To the current day, the construction of DTs that reflects the processes to a greater extent and is tightly integrated with them, remains a critical issue despite the advantages of the latter. Considering the fact that the structure of DT has a direct dependency on the utilization of DT in terms of algorithm comparisons, this paper comes up with what can be deemed as a comparatively intelligent method in construction and evaluation of DT. In order to achieve high realism in modeling of systems, it is suggested to build a new construction methodology that consists of the following policy optimization based on the deep learning algorithms and tunable parameters of the DT. However, there is the "Mean State Transition Error" or MSTE which is a standard measure of the performance of algorithms in such digital environments. In order to compare the performance of the suggested framework, the full simulation of the environment carried out is presented below; It can be seen in the simulation that proposed DT does not only reflect the real-world occurrences faithfully but also can form the basis for algorithm assessment. Therefore, the following directions are recommended to continue the research on the DT technologies to suggest what kind of theory enhancements can be made and the potential application across industries.

The study, Chen et al. (2024) pointed the establishment of Industry 4.0, computerized twins utilize computer models to mimic real-world marvels, altering businesses like mechanical computerization and generation administration. Data-driven procedures for making advanced twins on computerized computers with discrete-time information and finite-depth models are made conceivable by later improvements in machine learning. Nevertheless, this method has trouble modelling complicated system behaviour and misses the underlying continuous dynamics. Additionally, because the CPU and storage units are separated in digital computer design, frequent data transfers and Analogue-Digital (A/D) conversion are necessary, which greatly increases the time and energy needed. This work presents a memristive neural solver for ordinary differential equations (ODEs) for digital twins that can capture dynamics in continuous time and facilitate the modelling of complex systems using an infinite-depth model. They avoid the Von Neumann bottleneck by combining storage and computing in analogue memristor arrays, which improves speed and energy efficiency. By building a digital replica of the HP memristor that accurately extrapolates its nonlinear dynamics, they demonstrate their methodology empirically. Their approach is anticipated to produce a projected speedup of 4.2 times and a projected decrease in energy consumption of 41.4 times when compared to the most recent digital hardware, all while keeping an acceptable error margin. Furthermore, Using experimentally based simulations of Lorenz96 dynamics, they demonstrate scalability. Compared to traditional digital approaches, they anticipate performance advantages of 189.7 x energy efficiency and 12.6 x speed. Their innovation quickens the construction of digital twins by utilising entirely analogue computing's capabilities, providing a quick and effective way to satisfy Industry 4.0 expectations.

The primary objective of the examination executed by Guerrazzi, Mininno and Aloini (2024) was Worthouses are almost mandatory in nearly all supply chains and significantly affect the efficiency of the whole chain. The DT implemented in this work was built and validated on real data collected from plant sensors and information systems.

One of the best examples of its usage is the goal that directs it – it is aimed at assisting the manager of a particular warehouse in the determination of an SBS/RS picking strategy that would provide the most effective balance of the overall picking and outbound loading processes. The goal is to enable timely and economical distribution to the following nodes, as previously most warehouse research has focused on operational performance without considering its effect on downstream nodes. The study is based on a real-world case study of the logistics centre of a tyre distribution company and builds on previous work. Subsequently, three picking techniques that had different effects on outbound loading efficiency and picking were defined using the DT. After that, the DT was used daily to simulate picking and stocking procedures and supply the warehouse PLC with the recommended picking strategy. It was supplied with actual orders, machine, and rack availability. To draw further managerial conclusions, a number of demand scenarios have been examined. According to the results, the DT is a useful tool for supporting the performance balance of pickup and outbound loading.

The mission of the study carried out by Borodinecs et al. (2024) was In the structure guiding the European Union's (EU) pursuit of carbon neutrality, digital twins offer a promising method for managing and operating sustainable buildings. illustrated how to form and adjust building advanced twins with OpenStudio, an open-source building vitality modelling software. With its intuitive interface and powerful simulation features, OpenStudio makes it possible to model building systems and components in great detail. With OpenStudio Measures, users can alter simulation models and automate procedures to improve building performance. Precise documentation of a building's geometry, materials, schedule, and HVAC (heating, ventilation, and air conditioning) systems are needed in order to generate a digital twin of the structure. Issues with data accessibility and model correctness draw attention to how crucial modelling techniques are. In order to replicate various building operation conditions, editing the digital twin entails making changes to the EnergyPlus weather files and OpenStudio model files. Opportunities for modifying digital twin files using the Python programming language were taken into consideration. Digital twins have the capacity to optimise building system settings and simulate future building circumstances. To create a digital twin of a building, precise records on its geometry, materials, scheduling, and HVAC (heating, ventilation, and air conditioning) systems are required.

Metrics for Evaluating Operational Efficiency Improvements

Stary et al. (2022) Investigated that Digital Twins are virtual representations of Cyber-Physical Systems that allow for both ongoing observation and proactive functional enhancement of networked services, tangible goods, machinery, and equipment. This ability is crucial for identifying and investigating commercial prospects related to technological and organisational advancements, as well as expanding the range of applications that are pertinent to the system. Through executable behaviour models, Cyber-Physical Systems can be tested and used as Digital Twins prior to being deployed in their intended ecosystems, like smart cities. These models' construction allows for the consideration of both the horizontal and vertical integration of Cyber-Physical Systems (CPS) components, allowing for the consideration of specific system aspects such the effects of traffic pollution. The technological and methodological difficulties involved in creating and managing Digital Twins during system transformation operations are examined in this paper. Within the framework of human-centered modelling and development, they took into account integration breadth and depth, connection, organisational intelligence, validation, and implementation variability. By enabling the dynamic distribution of digital and physical components according to operational conditions, the approach enhances the digital representation of CPSs and expands our understanding of digital twins. An outstanding case study on traffic management demonstrates the practicality and effectiveness of the communication-centered strategy.

Lai (2023) looked into the conditions for building digital twins using machine learning for externally driven nonlinear dynamical systems. These digital twins allow one to keep an eye on the target system's "health" and predict when it will break. They demonstrate how the digital twins, using either a single or many reservoir computer systems, can carry out intricate monitoring and forecasting duties. Using model systems from the domains of ecology, optics, and climate, they have demonstrated that the digital twins are capable of performing continuous forecasting and monitoring with sparse real-time updates under nonstationary external driving, extrapolating the dynamics of the target system to unexplored parameter regimes, accurately predicting the dynamical evolution of hidden variables, adapting to various types of external driving, and extrapolating the global bifurcation behaviours to systems of varying sizes. Because of these characteristics, their digital twins are now sought after for important applications including tracking the condition of vital systems and predicting when they may fail due to environmental changes.

The findings pointed out that Jedermann et al. (2023) unlike previous offline simulation methods, data must be processed on the fly by one or more models in order to fully benefit from live or real-time sensor measurements. The concepts created under the generic name "digital twin" (DT) are most suited to meet this demand. They talk about these additional characteristics and the difficulties in moving from the Internet of Things (IoT) to fully utilising distributed sensing (DT) solutions. As an example, They use DT to remotely monitor fruit as it is being transported by sea. Changing over models into an updateable organize could be a basic errand that keeps the displayed representation and the physical thing in match up. Unused computer program arrangements for the basic and versatile improvement of an event-driven design for the association of a few models over a spilling stage are one on a very basic level novel angle of DTs. They display a strategy for overseeing the model's execution over a few stages of the fruit's physical life cycle. Iinvestigation of reaction times appeared uncovered that the server's capability to oversee over 100 DT occurrences per moment is satisfactory.

Challenges and Solutions in Implementing Digital Twins for Efficiency

The study, Mitkov et al. (2024) emphasized the quick drift of urbanization has given rise to complicated troubles within the organization of urban situations, enveloping everything from vitality utilization to natural measures and open wellbeing. As a result, the thought of "city advanced twins" has surfaced and could be a reasonable strategy for comprehending and controlling urban complexity. With the utilize of real-time information and reenactments, city computerized twins construct virtual forms of urban settings that permit partners to evaluate, advance, and choose on a run of angles of city life. City computerized twins intensely depend on Computational Fluid Elements (CFD), which gives devices to show discuss quality, contamination scattering, wind stream elements, and other angles of urban settings. The conceivable outcomes and troubles of consolidating CFD into city advanced twins are inspected in this think about. Conceivable outcomes incorporate raising natural quality, boosting open wellbeing comes about, and streamlining urban arranging and plan strategies. Nonetheless, challenges in information integration and quality, execution limitations, computational issues, and communication must be solved if CFD has to achieve its application potential in urban environment. In the context of urbanisation process and climate changes the application of CFD as a way of enhancing the DTs of cities has potential to help make these cities and the lives of their inhabitants more resilient, healthy and sustainable.

According to Hurley et al. (2024), semantic interoperability issues are brought on by the increasing use of DT in a variety of fields and industries. Although ontologies are a well-known approach to overcoming these difficulties, there is a chance that ontology representations will introduce new interoperability issues due to the complexity of the phenomenon. To mitigate these risks, they present and justify digital twin characterizations in the framework of the Common Core Ontologies, an expansion of the popular Basic Formal Ontology. Using examples of both digital and physical twin use cases, they offer a set of concepts and design patterns pertinent to the field of digital twins. By doing this, they offer a framework upon which more complex ontological content pertaining to and associated with digital twins can be constructed.

According to research conducted by De Domenico et al. (2024), Precision medicine is finding it more and more feasible to use digital twins (DTs), thanks to advances in artificial intelligence (AI) and massive data collecting, in addition to established biomedical techniques. But the use of huge datasets in black-box prediction models has drawbacks that may prevent DTs from being used more widely in clinical settings. They contend that generative models driven by hypotheses, especially multiscale modelling, are critical to improving the clinical relevance and accuracy of DTs and, consequently, have a major influence on innovation in healthcare. The transformational potential of DTs in healthcare is examined in this research, with a focus on how well they can replicate intricate, interconnected biological processes at various scales. They present a scenario-based modelling technique that facilitates the exploration of various therapy regimens and supports dynamic clinical decisionmaking by merging generative models with large datasets. By combining insights from digital medicine, quantitative biology, complex systems and network science, and big data and data science advancements to improve disease treatment and prevention, this strategy promises to significantly improve patient care.

The study, Hemdan, El-Shafai and Sayed (2023) revealed that Because of its developments in blockchain, cloud computing, IoT, IT, and communication technologies, What has attracted the researchers and organizations in the past years is the concept of the Digital Twin. It is therefore the goal of the DT to provide clear functional and physical descriptions of each part, asset or system involved. However, it is a very active taxonomy and generates huge amounts of data and information as the life cycle of the taxonomy progresses and becomes more complex. Similarly, digital twins promise to revolutionise and potentially even be a key component of Internet of Things (IoT)-based digital twin applications that ensure transaction immutability, reliable traceability, and accessibility while transferring value and data online in a fully transparent manner. Consequently, by offering improved security, transparency, and data integrity, the marriage of blockchain and IoT technologies with DT has the potential to completely transform a range of organisations. Subsequently, a overview on the cutting edge theme of advanced twins with Blockchain integration for different applications is displayed in this ponder, diagrams the challenges and potential ways for this subject's future investigate. In expansion, They offer in this paper an Online of Things-based design and concept for combining blockchain chronicles with advanced twins. This permits for the safe, decentralised, and momentary checking and administration of forms and physical resources. They too go over the troubles and limitations this association presents, such as interoperability, adaptability, and information protection concerns. In conclusion, They offer perspectives on the potential applications of this innovation within the future and conversation approximately conceivable investigate roads to assist the integration of advanced twins with blockchain chronicles based on the Web of Things. In outline, this consider builds up the basis for future investigate in this field by advertising a exhaustive examination of the conceivable focal points and troubles of combining blockchain innovation based on the Web of Things with advanced twins.

2.6 Improvement of Product Quality and Consistency

Tools and Techniques for Quality Improvement Using Digital Twins

The study conducted by Segovia and Garcia-Alfaro (2022) uncovered that a computerized twin (DT) may be a bunch of computer-generated models that speak to an real protest in a virtual setting. Actual and apparent need to communicate to convert/clone, predict, analyze, regulate and monitor state and activities of the real body within the virtual world. By offering information and system updates, DTs enable the development of new business models. In this work, they explore the formation of DTs. More precisely, they are concerned with figuring out (methodologically) how to design, produce, and link actual products to their virtual equivalents. They break down the problem into multiple steps, starting with the planning and selection of functional requirements, moving on to the integration and verification of the finished (digital) models. They also discuss experimental platforms for DT construction (including standards and protocols) and the real-time information flow between physical components and DTs. They have a talk and some unanswered questions at the end.

Evidence from the investigation Mohamed et al. (2023) suggested that Healthcare systems are intricate systems that require administration, control, optimisation, and effective and efficient operations in order to provide dependable, excellent, and reasonably priced healthcare services. Improving healthcare system management can be achieved in part by applying the concepts of healthcare systems engineering. Drawing upon engineering methods of analysis and synthesis, HSE does not view a healthcare organization as a system in isolation but undertakes to improve one or more aspects of the healthcare services delivered by the organization. Although healthcare organisations can benefit greatly from this strategy, there are numerous obstacles that prevent healthcare systems engineers from carrying out their role in an efficient manner. The appearance of computerized twin technology made numerous roads for enhancement within the operations of distinctive mechanical divisions. As a result, they can help in raising adaptability, cost-effectiveness, steadfastness, and quality. In arrange to help with different ranges of the frameworks, this think about explores how computerized twins can be utilized to upgrade the building forms and results of healthcare frameworks. The paper talks around a few of the troubles in making healthcare frameworks and how utilizing computerized twins can offer assistance to ease those challenges. The paper presents a conceptual system for leveraging computerized twins to move forward the practices and comes about of the range of healthcare frameworks designing, beside a discourse of the potential benefits of doing so. Moreover, The paper gives an examination of the suggestions of utilizing computerized twins for healthcare frameworks engineering, as well as a estimate for future investigate and advancement in this region.

The research Ali et al. (2023) outlined that A computerized twin (DT) could be a computerised show of an genuine framework or protest that's utilized to screen, evaluate, and improve its characteristics. Of specific prominence is a Subtype called Spatial Digital Twin (SDT) which concentrates on the physical question for an actual evaluation of the geometrical features and high-precision area and measurement details of the topographical environment for a comprehensive understanding of the spatial context. As a result of subsequent advancements in AI/ML, spatial breakthroughs, and other computer advances, the market for SDTs is anticipated to grow to $25 billions, serving a spectrum of applications. Most of the research that has been done so far is on DTs and frequently overlooks the spatial technologies that are required to build SDTs. The majority of the research that is currently available on SDTs focuses on examining their possible influence and opportunities across a range of application domains. Because developing an SDT is a multifaceted process including several spatial computing technologies, it can be challenging for practitioners and academics in this interdisciplinary subject to comprehend the fundamental aspects of the SDT's enabling technologies. They are the first to thoroughly examine several spatial technologies pertinent to the construction of a layered SDT in this research (from data collecting to visualisation). Four technological layers comprise the fundamental components of SDTs: (i) data acquisition; (ii) big data analytics & spatial database management systems; (iii) GIS middleware software, maps, & APIs; and (iv) fundamental functional components like visualising, querying, mining, processing, and prediction. Furthermore, they go over how to properly use contemporary technologies like blockchains, cloud computing, and AI/ML to enable and improve SDTs. In conclusion, they list many research possibilities and problems in SDTs. In addition to clearly separating SDTs from regular DTs and outlining their key technological components, this study also highlights unique applications for SDTs and provides a road map for their continued advancement, compete with challenges. It is therefore a valuable tool for SDT practitioners and academics.

The findings Ghorbani and Messner (2024) pointed out that between 60 and 80 % of a facility's lifespan costs are related to operations and maintenance (O&M). O&M can save time and money by becoming more productive and efficient with the use of digital twins (DTs). Originally developed for the aerospace industry, DT subsequently found its way into other sectors of the economy. Since DTs are unused to the Architecture, Engineering, Construction, and Operations (AECO) Industry, there's a part of deception with respect to this idea. In order to set up a shared understanding of DTs inside the AECO segment and encourage their selection, this article points to characterize DTs and offer a classification plot. A careful analysis of the writing was conducted in arrange to decide the current definitions and classification plans for DT. Subsequently, the fundamental components of definitions were distinguished employing a content examination. Utilizing the space dialect, the highlighted components were utilized to form an comprehensive and careful DT definition for the AECO industry. Similar to this, substance examination was utilized to look at pre-existing DT categorization structures and decide their constituent parts. A DT categorization structure utilizing space thoughts and wording was given for the AECO industry based on the identified components. The comes about were refined and approved by a arrangement of semi-structured master interviews and studies. DT experts with a variety of backgrounds from academia and industry made up the interviewees and survey respondents. The components of the proposed DT concept are virtual representation, data links between digital and physical objects, analysis, actuation, and update frequency. Three DT categories made up the categorisation structure: Digital Twin Prototype (DTP), Cyber-Physical System (CPS), and Digital Shadow (DS).

Case Studies on Enhanced Product Quality through Digital Twins

The objective of the research undertaken by Simchenko, Tsohla and Chyvatkin (2019) By bringing transparency to the supply chain, IoT is poised to transform it in terms of operational efficiency and revenue prospects. This research focuses on analysing the challenges and results of integrating IoT with digital twins. When a scientific framework for assessing the cumulative effect of faster adoption of digital twins is established, the competitiveness of a modern industrial business should increase and its growth may be attributed to it. Their research indicates that both concepts are firmly embedded and complimentary in the context of the modern industrial digital revolution for two reasons: 1) Big Data, within the IoT context fundamental elements are intrinsically worthless since these are made of massive data continues flowing in an unstructured format and are visualized based on different parameters. 2) Due to digitization this asset value will gradually shift towards a company's Digital Twins. Big data can be useful in addressing certain business problems at this point. In this way, IoT can be credited with helping to create Digital Twins, which are the most important resource for companies operating in the digital economy. From a methodological perspective, They can create multiple intermediary forms of digital standardisation inside the continuum "standardisation - technological breakthrough" by integrating these principles.

The target of the inquiry made by Somers et al. (2022) When creating dependable systems, digital twins' lack of testability presents a number of challenges. Physical couplings complicate the collection of test data, and complex models make it challenging to establish comprehensive testing requirements. They discuss causal inference-based testing in an attempt to overcome these issues, and they present a method that enables the representation of the correct behaviour of digital twins in causal graphs. These diagrams are then checked by using an efficient data set and counterfactuals. They demonstrate how this method may confirm established causal links inside a system and even identify a flaw that led to harmful conduct using an intriguing case study of a robotic arm. Their method limited this incorrect conduct to a single cause-and-effect connection between two variables. After demonstrating the effectiveness of this method through a case study, They examine its drawbacks and the difficulties in applying it to other industrial applications.

The principal objective of the study carried out by Jiang and Alkhateeb (2023) Accurate channel estimate or precise narrow beam adjustment are necessary for large-scale Multiple-input multiple-output (MIMO) systems to reach their full potential. On the other hand, high beam sweeping overhead and channel acquisition that rises with the number of antennas are typically associated with this. Potential solutions to these problems can be found in machine and deep learning, which have a great ability to learn from side information and previous observations. However, collecting large-scale datasets—which are required for training machine and deep learning models—is expensive in deployed systems. In order to address this problem, they provide a unique technique that minimises or even completely removes the MIMO channel acquisition cost using digital copies of the actual world. The suggested digital twin-assisted communication generates 3D models with precise ray-tracing that imitate site-specific channels and almost mimic the actual communication environment. Then, many communication chores can be made easier with the use of these channels. They also recommend machine learning for approximating digital copies and reducing ray tracing's computing cost. The digital twin-based suggested solution is evaluated through a case study focused on the position-aided beam prediction problem. The findings demonstrate that when a learning model is trained only on digital data, it may produce respectable results when applied to real-world data. Rapidly achieving near-optimal performance with a small number of real-world data points can also significantly reduce data collection overhead and fix modelling discrepancies between the digital and physical worlds.

Consistency in Production: Role of Digital Twins

The intent of the inquiry conducted by Busse et al. (2021) Modern multi- and intermodal supply chains have many opportunities for optimisation, but they also present a substantial control and maintenance issue. Digital twins have been proposed as a way to improve supply networks. They are currently exclusively utilised in specific supply chain sectors, though. This research presents a draft concept for a complete Digital Supply Chain Twin (DSCT) that can include a multimodal supply chain in its entirety. Such a DSCT enables various supply chain modifications in addition to modelling and evaluating a range of supply chain scenarios. Consequently, by spotting potential problems early on, the DSCT may strengthen multi- and intermodal supply chains in addition to optimising them. The main criteria that a DSCT needs to meet in order to be effective are covered in this paper, along with how a number of recently developed or soon-to-be developed information technologies can help meet these requirements. The final step towards creating a DSCT as described in this work is to propose a suggested high-level architecture for one.

Accordin to a study by Satyarthi, Pandey and Khan (2021) These days, system development is common, and it might be difficult to maintain the appropriate level of security and reliability. The majority of software developers, according to research, lack the skills required to create safe software systems. Along with adhering to the safe software development lifecycle, such knowledge ensures that the relevant security criteria are fulfilled. For engineers and developers, critical product demands are a continual source of concern. They must be tracked, monitored, and implemented. On the other hand, as technology advances, digitization presents a number of chances for more environmentally friendly system design and management. By using DT to update and maintain a dynamic digital representation of a physical system, a more realistic virtual replica of the system may be produced. We believe that digital twins are a more effective instrument for assessing the improved output and defined structure of safe software systems, as well as for putting them into practice for faster processing and more efficient administration. This article describes a process for using digital twins to build and manage secure software. It also explains how it functions and how software systems might use it to increase security.

The mission of the study carried out by Abusohyon et al. (2021) By applying Advanced Twins to digitalize commerce forms, associations can superior adjust themselves with the quick progression of innovation and accomplish superior comes about understanding how the imaginative prepare, which shapes the premise of Advanced Twins, influences the usefulness of the other components and the conclusion item is fundamental to amplifying their use. This think about centers on the need of a exhaustive establishment for making the imaginative stage of advanced twins. In arrange to make the suitable system, a subjective experimental strategy was utilized to assemble information through interviews with individuals who have mastery within the field of advanced twins. The interviews pointed to uncover all significant subtle elements with respect to this stage, counting the sorts of substances included, potential challenges and impediments, and successful arrangements to overcome them. The recommended framework's auxiliary component always prepares the framework for adjustments with the goal of embracing internal advance. All businesses who wish to start the method of carefully speaking to physical resources or those who work with advanced twins and wish to improve the interoperability of their frameworks can use the study's discoveries as direction.

Chen et al. (2023) presented the concept of a five-dimensional advanced twin demonstrate called the “Plant Factory Transplanter” (PFT) based on inquire about of plant manufacturing plant transplanters. The conflictual relationship between several factors when simulating plant factory transplanters, the disparity between model simulation and actual model, and problems in data acquisition and assessment are the core components of the PFT. Therefore, connecting the interactions of a person in social media, utilizing twin data, virtual and, physical components as well as the real environment distinguishes the PFT five-dimensional digital twin beyond just the three-dimensional model. This research analyses the methods and interpretations of the development of the PFT five-dimensional model from five perspectives which include PFT virtual entity, the service-oriented aspect of PFT, twin data of PFT, the physical aspect of PFT, and the connections of PFT. The results of what happens when each link is clicked is also displayed. Last of all, we illustrate several case studies of using the PFT digital twin five-dimensional model. The five-dimensional modelling approach to plant manufacturing transplanters based on digital twins can be used to control the transplanters’ state and assess the efficiency of transplantation from a remote location. By addressing issues like limited flexibility and challenging physical model updates, this approach enhances the effectiveness of configuration parameter optimisation and monitoring. Additionally, the control interface more naturally represents the created virtual entities, greatly lowering the need for related professional expertise on the part of equipment operators. It is anticipated that the suggested five-dimensional digital twin model will be further improved and optimised in the future, with application scenarios and creation tools being investigated. Additionally, application research will be done to satisfy various application requirements.

2.7 Integration of EPC Principles with Digital Twin Technology

According to Suhail et al. (2022) Industrial processes use sensory data to evaluate performance, identify risks, and make decisions. Data that is both collected and transmitted in a trustworthy manner is essential for drawing useful conclusions. This means that for the physical data to be considered reliable, it must pass through many sensors and their field of view should have some intersection. As a result, the data cross-validated may be kept in the blockchain to ensure that data remains credible. Once reliable information has been secured on the block chain, various events relating to the life cycle of an item may be popularized into data-intensive solutions for manageability, diagnostics, and enhanced control. For this reason, by spotting mistakes and proposing fixes some time recently vital events, Computerized Twins (DTs) can be used to form brilliantly deductions from information. Utilizing blockchain to enable DTs in mechanical utilize cases tackles three principal issues:

The prerequisite for prescient support, conflicting information the Future Is Here - IDBS ELN Software - Best-in-class platform dispersal, and conflicting data repositories. They present a comprehensive examination of the foremost later research results on blockchain-based DTs in this study, accentuating the most points of interest of their application. They investigate a versatile engineering for blockchain-based disseminated records DTs, based on current inquire about patterns. They underscore how blockchain-based DTs utilize artificial intelligence (AI). They too conversation approximately continuous inquire about and usage challenges with blockchain-supported DTs that require more think about.

The key purpose of the investigation undertaken by Stennikov et al. (2022) the complex courses of action of integrated energy systems (IESs), the assortment of gear they use, and the complexity of IES plan stems from the run of scientific models and particular computer program required to demonstrate them. Advanced twins permit for the demonstrating of different IES arrangements in virtual space. This leads to the extraction of an perfect IES alternative, which is at that point utilized to construct or expand an real IES. The essay suggests applying computerised twin development techniques to address the issues with the IES plan. In this paper, the authors apply the new methodological approach for constructing the IES with the use of its digital twin developed by the authors. I described the following approach: a set of approaches to using the Model-Driven Engineering (MDE) for creating advanced twins, ideas about how to organize computational handle based on the multi-agent approach, as well as some ideas about what kind of plan an Integrated Expert System (IES) may have based on its advanced twin and an algorithm of how this plan may be created, and finally design of the computer program stage for creating advanced twins. This analysis demonstrates the computational trial applying the software application of the IES virtual twin components of a test energy supply conspiracy.

Darian and Kontorovych (2021) looked into the expanding complexity of asset management and ensuring the operational unwavering quality of electric control gear requires the creation and usage of advanced twins, which request particular care all through the equipment's life cycle. This paper addresses the concepts and new needs for the creation of better electrical control equipment twins based on an investigation of these problems. The basics of developing component functions, analyses, and graphics for digital twin architecture are covered in the article. The major technological specifications for virtual replicas of electric power equipment are described.

The objectives of the study by Kichatov, Prosochkina and Vorobyova (2023), aim to define the steps involved in generating a digital twin to optimise the production of oil and gas chemicals, as well as the principles involved in creating digital twins of operational technological units, such as the liquid-phase alkylation of benzene with propylene. A sophisticated high-level system analysis is performed on the chemical and technological system, which is made up of a reactor, separator, heat exchangers, mixer, rectification columns, and pump. Using UniSim® Design software, data were gathered and the main process parameters were calculated to characterise the isopropylbenzene production unit's functioning. A neural arrange demonstrate was made and prepared taking into consideration factors that influence the alkylation response prepare, item division, and financial investigation. A microcontroller model of the method was made, and measurable procedures were utilized to affirm the exactness of the computations. The created prescient neural arrange demonstrate and its creation calculation can be stacked onto a microcontroller, empowering real-time assessment of the financial proficiency of plant operations as well as robotized enhancement based on factors like reactor weight, handle temperature, crude fabric composition, and plant innovative mode.

Technology Acceptance Model (TAM)

Davis's (1989) “Technology Acceptance Model” (TAM) serves as a hypothetical system for exploring components that impact people's openness to and utilization of novel advances Alshammari and Rosli (2020). It proposes that a user's purpose to use innovation is significantly impacted by the user's recognition of how advantageous and how simple the innovation is to utilize. TAM includes a part of bearing on the subject of utilizing DTs to move forward operations. It helps our understanding of the mental variables at play when laborers at an association either stand up to or eagerly embrace DT innovation (Zaineldeen et al., 2020).

The TAM may be successfully utilized within the examination of investigate request relating to the money related maintainability of associations, the appraisal of Key Execution Pointers (KPIs), as well as the investigation of different devices and procedures pointed at upgrading item quality (Villazón et al., 2020). The evaluation of employees, managers, and stakeholders' perspectives on the efficacy of DTs in promoting operational efficiency Vering et al. (2019), cost reduction Farsi et al. (2021), and product quality Zhang et al. (2020) is of fundamental significance. By comprehending client discernments, this hypothetical system can give profitable bits of knowledge into the likelihood of accomplishing compelling selection of DTs and the acknowledgment of return on venture (ROI) (Callcut et al., 2021). Furthermore, it can help within the distinguishing proof of potential impediments and strategies to progress client adequacy and usage.

Resource-Based View (RBV) Theory

Birger Wernerfelt (1984) and Jay B. Barney (1991) the scholastics who have contributed to the Resource-Based See hypothesis, which looks at how businesses may accomplish and keep up a competitive edge through cautious arranging and execution (Freeman et al., 2021). Understanding how DT innovation may be seen as a critical authoritative asset within the setting of DTs and operational brilliance can be investigated by means of the focal point of RBV hypothesis (Attaran & Celik, 2023).

The points in ranges like operational effectiveness enhancement, DT advancement, and EPC integration may be finished with the help of the utilize of RBV hypothesis (Jegan Joseph Jerome et al., 2023). As an illustration, if built and used appropriately, DT technology may be a beneficial tool for product quality Zhang et al. (2020), operational efficiency Vering et al. (2019), cost reduction Farsi et al. (2021), and ROI (Caccamo et al., 2022). The thought accentuates the noteworthiness of steady mechanical progression in light of the company's display assets and capabilities.

In rundown, the hypothetical establishment of this think about utilizes the RBV hypothesis to evaluate DT innovation as a strategic asset for making and keeping up competitive points of interest. The TAM is utilized to gage client sees and worthiness. This study's overarching objective is to combine these thoughts and offer knowledge into how businesses might use DTs to boost their benefits, boost productivity, and beat their competitors. The ponder employments this method to see at the impacts of DT selection and integration for businesses looking to improve their operations efficiencies and other variables.

2.8 Digital twins and their characteristics

According to Tao et al. (2018), DT comprises of three components- a virtual item, a physical item, and connective information that joins the two. DTs may be used in a assortment of businesses and innovative areas, as has been detailed. They have also been found to have a variety of qualities that are valuable Rasheed, San and Kvamsdal (2020) and provide excellent chances for merger and cooperation of physical and digital worlds (Liu et al., 2019; Fuller et al., 2020). A number of application areas, counting keen cities, fabricating, healthcare, and flying, have as of now made utilize of DTs (Barricelli et al., 2019).

Information are basic for upgrading arranging, comprehension, and decision-making within the connected world of nowadays. The capacity to alter a advanced show and speedy advancement are two characteristics of DT (Aheleroff et al., 2021). The capacity to mimic and test thoughts some time recently taking genuine activity makes these two things accommodating for investigation (Grieves & Vickers, 2016; Kaur et al., 2020). In terms of investigation, DTs moreover see at how diverse parts of the framework connected, make "what in the event that" scenarios, Dissect how potential changes might influence the system's usefulness and make a advanced copy of the physical question or system's condition and conduct (Tao et al., 2018). DTs can unravel issues in a way that leads to critical real-life arrangements with certain recreation models and exploratory components (Khajavi et al., 2019).

With the help of cutting-edge innovation, DTs may transmit information between genuine and virtual universes, permitting clients to benefit from highlights that screen, direct, figure, and maintain operations (Khajavi et al., 2019; Aheleroff et al., 2021). Users are employees, management, operators, designers, maintenance personnel, etc. For example, managers might use real-time performance measures data and IoT-enabled dashboards to monitor and control the implementation of change from a distance by relying on the directive elements of DTs (Aheleroff et al., 2021). DTs can duplicate the present state of physical objects, processes, or systems and forecast significant changes and future behaviours with the use of sensor updates and historical data (Barricelli et al., 2019; Grieves & Vickers, 2016; Qi et al., 2021). They can also provide guidance on issue diagnosis, preventative maintenance, and performance analysis. Real-time operational training instruction is another piece of advice that DT users may get. which enables them to study in virtual reality without worrying about the repercussions of failing (Tao et al., 2018).

2.9 Techniques and tools to leverage digital twins

Madni, Madni and Lucero (2019) offered a broad vision and justification for DT technology integration within MBSE. They discussed the advantages of combining DTs with IoT and system modelling to enhance MBSE and provided instances of DT technology's application and benefits in various industries. The recommendation to include DT technology in the MBSE methodology and experiment testbeds comes to a conclusion. Mihai et al. (2022) provide a comprehensive overview of the DT technology, including its key enabling technologies, challenges, prospects, and wide-ranging applications. They highlighted the importance of DTs, their design goals, limitations, and their significance across various industries, including infrastructure and healthcare. They discovered that DT technology makes it possible to create digital copies of physical systems for real-time monitoring and analysis by integrating IoT, AI, 3D modelling, and other cutting-edge technologies. Jiang et al. (2021) analysed advanced DTs, with a particular emphasis on their application to smart manufacturing and, more specifically, plant-wide optimisation. They concluded that modern industry uses DT techniques to bring a wide range of occupations online, including all aspects of manufacturing and assembly, advertising and sales, and research and development. As more people become aware of the financial benefits of DT adoption, the technology is poised to become the backbone of the Industry 4.0 (I4.0) era, driving forward vital processes like industrial restructuring and upgrading while also opening up exciting opportunities for brand new, high-value services.

Autiosalo et al. (2020) distilled the shared characteristics of DTs from the existing literature and proposed an analytical approach for doing case-by-case comparisons of DTs. This technique is used to ensure the characteristics actually exist and it has room for improvement. They conform the data to a feature-based DT framework (FDTF) that may be used to design and organise DTs globally. The framework is composed of three main tenets: Three fundamental ideas underlie DT theory: (i) the notion that every DT is made up of a specific set of features; (ii) the capacity to compare DT instances using those features; and (iii) the capacity to integrate those features using a data connection feature in order to more efficiently build future DTs. Their discovery that feature combinations vary throughout implementations and that the traits are recognisable in previous DT implementations is noteworthy. Experts advise utilising these traits to increase the productivity and usefulness of DT conversations. Additionally, they offer a standardised process for creating DTs Davila Delgado and Oyedele (2021). They could learn more about DTs in the built environment by studying the structure and operation of DT systems from manufacturing literature. DT, CPS, and BIM are first thoroughly compared and analysed in this work. After that, fifty-four scholarly and commercial papers' structural and functional descriptions were carefully examined and assessed. Three different categories of functional models and three different types of structural models were discovered. They also looked at the literature on DT maturity models. Six types of DT process models (DT creation, optimal operations, asset monitoring, simulation and prognosis DT synchronization, and optimised design) and four categories of DT conceptual models were identified as a result of the literature study's findings. Modifications are necessary, even though model-service-based approaches are most transferable to the physical world. The most generally relevant models for AECO use cases are those involved in the prognosis and simulation of processes.

2.10 Digital Twins in engineering and manufacturing firm

Olivotti et al. (2019) aimed to design and execute a system of installed base management specifically related to manufacturing that utilizes sensor and installed base information in order to maximize up time and minimize downtime. They were able, in turn, to implement a working model of fundamental management and then put it into operation, using real data from a test machine. This method helps to increase the availability of machines. The research also formulated design principles for developing and implementing such systems, enabling broader applicability. Tao et al. (2019) analysed cyber-physical systems (CPS) and DTs from various perspectives to better understand their differences and correlations. Both DTs and CPS are integral components in achieving cyber-physical integration, a critical aspect of smart manufacturing. The researchers draw the conclusion that cyber-physical connection and integration in production are crucial to the success of smart factories. The conceptual similarities between CPS and DTs are clarified through this work's examination of these two phenomena from contrasting theoretical viewpoints. Using the idea of Skin Model Shapes as a foundation, Schleich et al. (2017) provided a thorough reference model that can be used in both design and production as a DT of the actual product. Model conception, representation, and implementation were addressed in this context, as well as applications across product life cycles. They came to the conclusion that a crucial competitive advantage for contemporary manufacturing organisations is the capacity to evaluate the effects of decisions regarding products, processes, and customer service using virtual models. In the DT's vision, a real artefact and a collection of similar virtual models are intertwined.

Wagg et al. (2020) studied the situation of DTs at the moment in the engineering dynamics application field. Important steps that illustrated the transition to a DT were data-augmented modelling, system identification, verification, and validation. Utilising the production system's DT, Kunath and Winkler (2018) researched the technique for managing orders and their potential applications of a decision-support system. They recognised the significance of digitalisation, CPS, and DT in addressing the evolving needs and challenges faced by manufacturing companies. The focus is on enhancing order management through this innovative approach.

2.11 Key Performance Indicators (KPIs) for Operational Excellence

Moktadir et al. (2020) identified and prioritised KPIs for operational excellence in the context of sustainability, specifically in the field of the leather products industry in an emerging economy. By examining existing scientific literature and consulting with experts, the study seeks to categorise and prioritise KPIs, with a focus on supporting successful operational excellence practices in the supply chain of emerging economies. The findings highlight the importance of KPIs related to "Management" in driving operational excellence toward sustainability. Dwivedi (2020) explore how businesses can use times of economic crisis as opportunities for achieving business excellence. The focus is on improving strategic planning to enhance customer and stakeholder satisfaction while addressing economic challenges. In order to achieve business excellence during economic downturns, the study emphasises the importance of putting operational business principles like "Total Quality Management" (TQM), Six Sigma, and Lean manufacturing systems into practice. The key takeaways include cost savings, process improvement, quality sustainability, and enhanced staff and management performance. The study highlights the potential for businesses to not only survive but also strengthen their position in the industry by reframing economic crises as opportunities for strategic planning improvements. According to Dennert et al. (2018), Optimizing the effectiveness of production processes is one of the key objectives of any manufacturing organisation. Finding the proper KPIs and their linkages is a crucial requirement for such improvement. Providing accurate data from the whole manufacturing system is another requirement. In the study, Dennert et al. (2018) demonstrates which aspects a »Web-Based Enterprise Management« (WBEM) server can be easily adapted to provide homogeneous runtime data from production and IT systems with regards to a use case from the logistic scenario. Therefore the WBEM/CIM has incorporated the link models, business process model such as BPMN and information model for ISO 22400 KPIs. Another study by Chiarini and Kumar (2021) examined the potential for integrating I4.0 technology with Lean Six Sigma (LSS) techniques and concepts. Through the grounded theory technique, a new pattern for operational excellence is to be developed. In addition to direct observation of activities related to I4.0 and LSS integration at one of the chosen case organisations, data collecting entailed interviewing Italian manufacturing managers in 10 case organisations. The study's findings are consistent with early research that suggests LSS can provide a framework for successful I4.0 application outcomes. The integration calls for both a vertical, end-to-end integration and the redesign of mapping tools. The latter needs organisation to re-engineer ERP modules, but the true end objective of horizontal integration is to achieve Autonomous Process Synchronisation, which is a complete automated synchronisation of the processes. Furthermore, new analytics at all levels must be developed in order to handle the data collected from production processes and offices. In Marek, Schuh and Stich (2020) found KPIs that are applicable to a wide range of manufacturers. Operational performance aspects including efficiency/cost, time, quality, and adaptability are the focus of the examination. To this end, 180 publications were analysed systematically in order to determine the most commonly used KPIs in the literature. Eleven KPIs were then developed from the quantitative and qualitative data that followed. Based on these key performance indicators, researchers may evaluate the company's operations as a whole. Using a standard set of KPIs makes it feasible to make comparisons between businesses, laying the groundwork for optimisation across organisations. In research by Ante et al. (2018), the “Performance Measurement System” (PMS) of a lean manufacturing system is intended to be described as a tree-like structure of KPIs. In order to provide responses at tactical, strategic, and operational levels, the KPIs and the measurement components supporting them are defined and organised in a multi-level hierarchy. One example of the interdependencies between high-level decision variables, KPIs, and their measurement components is the "Bosch Production System" (BPS) (Richter et al., 2023), which is utilised by a major multinational manufacturer in the automotive industry. KPIs' significance in the I4.0 is also illustrated, as well as how they support, handle, and evaluate the implementation of smart manufacturing efforts.

2.12 Research Constructs Creation and Scale Justification

The survey instrument consists of a carefully designed number of questions to comprehensively assess the impact of Digital Twin (DT) technology across multiple organizational domains, such as financial viability, operational efficiency, and product quality. Each category has been selected based on the specific objectives of the study, with the intent to capture detailed insights on how DT adoption affects key performance indicators (KPIs) in engineering and manufacturing. The number of questions is balanced to ensure that all relevant facets are covered without overwhelming respondents, ultimately allowing for a robust analysis of the multidimensional benefits and challenges of DT technology. Based on pretests and literature on survey timing, it is anticipated that respondents will take approximately 5-10 minutes to complete the survey, which aligns with recommended survey lengths for maintaining respondent engagement while gathering substantial data.

A Likert scale is a very quick and easy-to-run type of survey that can be sent through all modes of communication. They provide a universal method of collecting data, which means it is easy to understand. In this study, A 5-point Likert scale was chosen for this survey over other scales, such as 3-point, 4-point, or 7-point scales, to provide a balance between granularity and respondent cognitive load.

A respondent's absolute agreement with the motif of the topic may lie between the two descriptive options provided on a 5-point scale. On repeated administration, he/she may differ in choosing one of the options, e.g. 3 instead of 4, when the person thinks in between the two of the response options on 5-point scale. A 7-point scale may eliminate this problem up to an extent by eliciting retrieval beyond the utmost level of agreement provided by a 5-point scale, the dilemma of choosing between the two undesirable points on 5 points. Hence, this dilemma of forced choosing between two equally undesirable points imposed by the 5-point Likert scale may be addressed up to an extent by offering more choices (in between) by a 7-point scale (Pearse, 2011). The provision of a number of scale points, 5 points or 7 points, would be more engaging to the minds of respondents when the items on the scale carry the statement of ideas near the truth of the universe for both the participants and the surveyor. It may create the ‘curves of reliability’ around the ‘zenith of validity’ (Finstad, 2010). Research supports the 5-point scale as a reliable and valid measurement tool that maintains a manageable response burden while effectively differentiating between levels of agreement or disagreement (M. Zhang, 2023). Additionally, a 5-point scale allows for a neutral midpoint, accommodating respondents who may be ambivalent or lack strong opinions, which is crucial for unbiased and comprehensive data collection (Joshi et al., 2015).

In the Survey Construct section of the literature review, the selection of a 5-point scale will be justified based on these considerations, supported by literature that validates this approach as appropriate for complex topics like DT adoption in technical fields. Some limitations of this design are recognized, including potential challenges in maintaining respondent focus and limitations in capturing highly granular attitudes. These limitations, however, are mitigated by the survey’s moderate length and balanced question distribution, which aim to collect insightful data without contributing to survey fatigue or response bias.

CHAPTER III:

METHODOLOGY

3.1 Overview of the Research Problem

As engineering and manufacturing organisations operate in more challenging contexts, they reach for a major barrier they need to manage to ensure organisational change. This is the challenge of acquiring the necessary Compounding systems. These complications are driven by several variables including: The growing scientific expectations in customer relations in availing customized products (Krishnamurthy & Kumar, 2015), the expanding environmental regulations, and the escalating competition in world markets. The goal of continuing running efficiency as the business strategic goal is emerging to be influential in expanding numbers of organizations in response to the issues.

Potential management strategies for achievement of the above goal include the implementation of digital twins (DTs) is a potentially fruitful approach that might be used to accomplish this goal. DTs, referred to as the newest technologies, seem very reasonable to serve the purpose of enhancing the quality of the product and reducing costs at the same time as well as driving the operational efficiency of business (TWI, 2021). However, to date, there is a vast number of gaps in knowledge concerning the ways of achieving the maximum beneficial impact of adopting DTs in terms of economic and business operations.

This study's overall goal is to fill this gap through the identification of the economic feasibility of DT adoption as well as quantification and evaluation of DT's measurable economic benefits. Due to their abilities to be the replicas of actual assets, processes, and systems, DTs enable monitoring, analysis, and optimisation efforts be accomplished in real time. DTs enable decision-making, which is based on data to enhance various indicators of performance in businesses. This is done through role playing of different scenarios and results or consequences. The other research objectives include quantitative measurements of the return on investment on DTs mainly in the areas of accurate equipment maintenance, time and other resources to include optimum utilization of resources attained through reduction of time losses.

The study will also establish how DTs impact on the Key Performance Indicators (KPIs) that are critical in delivering operation success. Other examples of KPIs as suggested by Ishaq Bhatti and Awan (2014) include the efficiency of the production process, quality of products and satisfaction of consumer. Moreover, the approaches for enhancing manufacturing processes and the application of such processes using Digital Twins will be examined and described as a part of the study. To achieve this, one needs to find out how DTs can be incorporated into the existing systems and processes. For instance, DTs can apply analytical competence to tasks of inventory management, thus being able to anticipate future demand and adjust supply line operations. This can be made possible via the application of advanced analytics. Also, they can improve quality assurance since they can determine any defects at a more initial stage of the manufacturing process, thereby cutting on costs through providing means of avoiding more waste and unnecessary work. Besides, regulating and sensing pollutants and energy in real-time, DTs can help with compliance to the needed environmental standards.

Moreover, the study will explain the challenges and barriers to the large-scale adoption of DT such as; the costs of implementing DT solutions; call for DT specialists; and connecting with existing systems. The goal of this research therefore is to offer recommendations to emerging markets that seek to compete in a market environment that is fluid and ruthlessly competitive to several firms. These findings will, ultimately, contribute to the existing literature on the topic of concern which is digital transformation in engineering and manufacturing. They will also make suggestions on how organisations can deploy technological advances as ways of optimising operations and sustainable profits, customers in a business.

3.2 Operationalization of Theoretical Constructs

To provide an empirical assessment of the current study theoretical constructs, a detailed and structured questionnaire is developed to capture several aspects of the DT technology adoption issue as well as the impact on organizational performance. The survey focuses on several key areas:

Adoption of Digital Twin Technology assesses the perceived importance of DT technology for enhancing operational efficiency, fostering interdepartmental collaboration, and improving decision-making processes. It also evaluates the challenges in integrating DT technology and the effectiveness of employee training.

After this, the dimension of **Financial Viability** gauges perceptions of DT's impact on financial health, including its potential to yield a favorable return on investment (ROI). It addresses whether DT adoption is seen as beneficial or detrimental to financial viability and economic benefits. Then, **operational excellence** is measured through key performance indicators such as customer satisfaction, revenue growth, productivity, quality control, and cost efficiency. The survey examines the positive impact of DT technology on these KPIs.

In the next part, **Production Process Optimization and Cost Reduction** evaluates how DT technology helps identify bottlenecks, optimize resource utilization, and achieve cost savings. It also assesses the communication of these benefits within the organization. **Integration of Engineering, Procurement, and Construction (EPC) Principles** measures the integration of EPC principles with DT technology, focusing on improvements in project planning, forecasting accuracy, and overall project efficiency. Overall **Operational Efficiency** evaluates enhancements in manufacturing processes, reduction in production downtime, improved resource utilization, and overall equipment effectiveness (OEE). At the end, **Product Quality and Consistency** measures DT's impact on maintaining product quality, reducing defects, meeting customer specifications, and improving traceability.

Each construct is measured using a 5-point Likert scale to capture respondents' agreement with various statements, providing a detailed understanding of DT technology's impact on organizational performance.

3.3 Research Purpose and Questions

The primary aim of this study is to investigate and demonstrate how Digital Twins (DTs) can be effectively leveraged to enhance operational excellence in the engineering and manufacturing sectors. More specifically, the following research questions need to be addressed:

- **RQ1:** What are the distinct economic advantages of applying digital twin technology across different industries, and how can the return on investment be calculated and evaluated?
- **RQ2:** What KPIs are most important for evaluating how digital twins affect operational excellence, and how do they change depending on the operational environment and industry?
- **RQ3:** What are the most effective methods and strategies for optimizing production processes and reducing costs through the use of digital twin technology in manufacturing and industrial settings?
- **RQ4:** What are the approaches that contribute to increasing the overall operational efficiency?
- **RQ5:** What are the most effective tools and techniques to leverage digital twin for improving product quality and consistency?

- **RQ6:** How can digital twin technology be integrated with EPC principles to enhance project efficiency?

3.4 Research Design

The current research work has adopted descriptive and quantitative research approach in establishing the application of DTs to enhance the operational effectiveness in engineering & manufacturing industries. To produce solid proof of the operational and economic effects of DTs, Cynthia dos S. Hentschke, Márcia Elisa S. Echeveste (2021) the methodology will centre on the gathering and statistical analysis of empirical data.

A structured questionnaire survey aimed at important stakeholders in engineering and firms will be the main method used to collect data. The managers, engineers, and IT specialists who work closely with the deployment and application of DT technology will be among these stakeholders (Li & Shi, 2021). Employing an empirical research approach, the study presented a positivist understanding of how DTs may be utilized to uplift production processes and product quality and correspond with EPC principles for the improvement of project effectiveness.

The design of this study is well aligned with the recommendation made for a broad and detailed empirical investigation of the DT technology in the sector. The findings of this study, therefore, is useful information that can be used to inform improvements to operations and strategic planning in the sector. Thus, it is expected that the findings will significantly extend the knowledge about DTs and offer valuable recommendations for increasing productivity and competitiveness in the manufacturing and engineering industries.

3.5 Population and Sampling

By emulating the architectural plan of the physical aspects, digital twins help in learning and controlling systems within and between organizations for improved performance. To test the above supposition, a survey study conducted with approx. 300 participants, and the participants include individuals working in different fields of engineering and manufacturing (Wang et al., 2022). Thus, such professionals as SCM, manufacturing, smart cities workers, engineering etc., are considered in this study as they know about the usage of digital twins or make decisions about their implementation. Thus, using a convenience sampling technique, the sample was selected based on the convenience.

When using this method, the study able to detect the nuances of implementing Digital Twins and the effects of their use, as well as include a broad range of participants' opinions (Lei et al., 2023). In order to study the perceptions, issues, advantages and effectiveness of the implementation of the DTs in enhancing operational effectiveness, close ended questionnaires were developed using 5-point Likert scale.

For the purpose of final sample size calculation, a 95% confidence level and a margin of error of 5.5% were selected, which are typical standards in survey research for reliable results (Ramachandran & Tsokos, 2020). A Z-score of 1.96 corresponds to the 95% confidence level, indicating that the results are expected to be within the margin of error in 95 out of 100 cases if repeated under the same conditions.

$$n = \frac{z^2 \times \hat{p}(1-\hat{p})}{\varepsilon^2}$$

Where,

- **Confidence Level:** 95%
- **Margin of Error:** 5.5%
- **Z-Score:** 1.96

Based on these values the final sample size was considered as 318 respondents for this research work.

3.6 Participant Selection

The participant selection of this study was done by following the below given criteria:

Table 1 - Inclusion and Exclusion Criteria

Participant Selection Criteria	Inclusion Criteria	Exclusion Criteria
Industry Sector	Manufacturing, Healthcare, Smart Cities, Supply Chain Management	Other sectors not specified
Role/Position	Engineers, IT Specialists, Managers, Executives	Administrative staff, non-decision-making roles
Experience with Digital Twins	Direct experience or decision-making authority in the implementation or use of Digital Twins technology	Lack of experience or involvement with Digital Twins
Organizational Level	Professionals from entry-level to senior management	Consultants or external advisors
Geographical Location	Global representation with a focus on diverse regions	Limited to specific geographical areas
Company Size	Small, Medium, and large organizations	Sole proprietorships or very small businesses
Years of Experience	Varied years of experience to capture insights from both seasoned professionals and newcomers to the technology.	Limited to professionals with extremely high or low years of experience

Ethical Considerations	Compliance with ethical guidelines and consent to participate in research.	Ethical violations or non-compliance with research protocols
Language Proficiency	Proficient in the survey language (English)	Language barriers preventing understanding of survey questions or requirements

3.7 Instrumentation

The following scale were evaluated based on the given survey instrument:

1. **Adoption of Digital Twin Technology:**

Statements	**1**	**2**	**3**	**4**	**5**
Digital twin technology is essential for enhancing operational efficiency in organization.					
The use of digital twin technology has increased collaboration among different departments in organization.					
We have encountered challenges in integrating digital twin technology with existing systems in our organization.					
The adoption of digital twin technology has improved our organization's decision-making process.					
Training and upskilling employees for the use of digital twin technology has been effective.					

2. **Financial Viability:**

Statements	1	2	3	4	5
Digital twin adoption is detrimental to our organization's financial viability.					

I believe that adopting digital twins can have a positive impact on our organization's financial health.					
The financial benefits of implementing digital twins are questionable.					
Digital twins are likely to yield a favorable Return on Investment (ROI) for our organization.					
I am confident that digital twin adoption will result in economic benefits for our organization.					

3. Operational Excellence (Measured KPIs):

Statements	1	2	3	4	5
Customer Satisfaction:					
The implementation of digital twins has a positive impact on customer satisfaction within our organisation.					
I am confident that digital twin adoption will lead to improved customer satisfaction for our organisation.					
Digital twins play a significant role in enhancing customer satisfaction in our organisation.					
Revenue Growth:					
Digital twins contribute to revenue growth in our organisation.					
I am confident that implementing digital twins will lead to increased revenue growth for our organisation.					
The adoption of digital twins positively affects our organization's revenue growth.					
Productivity:					
Digital twins enhance productivity within our organization.					

I am confident that digital twin adoption results in improved productivity for our organisation.

Digital twins significantly improve productivity in our organization.

Quality Control:

Digital twins positively affect our organization's quality control efforts.

I am confident that implementing digital twins results in better quality control within our organisation.

The adoption of digital twins leads to improved quality control in our organization.

Cost Efficiency:

Digital twins lead to cost efficiency in our organisation.

I am confident that digital twin adoption results in improved cost efficiency for our organisation.

Digital twins significantly improve cost efficiency in our organisation.

4. Production Process Optimization and Cost Reduction

Statements	1	2	3	4	5
Digital twin technology has helped in identifying bottlenecks and inefficiencies in our production processes.					
We have been able to optimize resource utilization (e.g., manpower, machinery) through the insights provided by digital twin technology.					
The adoption of digital twin technology has resulted in cost savings related to inventory management and stock control.					
Our organization has seen a reduction in production-related costs (e.g., material wastage, rework) since implementing digital twin technology.					

The benefits of production process optimization and cost reduction through digital twin technology have been communicated effectively within our organization.					

5. Integration of EPC Principles

Statements	1	2	3	4	5
The integration of EPC principles with digital twin technology has improved project planning in our organisation.					
EPC integration with digital twin technology has increased the accuracy of project forecasting and budgeting.					
The integration of EPC principles with digital twin technology has required additional training for project teams.					
Our organization has a clear strategy for maximizing the benefits of integrating EPC principles with digital twin technology.					
Overall, the integration of EPC principles with digital twin technology has improved project efficiency.					

6. Overall Operational Efficiency

Statements	1	2	3	4	5
Digital twin technology has improved the efficiency of our manufacturing processes.					
We have seen a reduction in production downtime since implementing digital twin technology.					
The use of digital twin technology has improved resource utilization in our organisation.					
We have experienced an increase in overall equipment effectiveness (OEE) since adopting digital twin technology.					

Overall, digital twin technology has enhanced the performance and effectiveness of our organization's operations.					

7. Product Quality and Consistency					
Statements	1	2	3	4	5
The use of digital twin technology has helped in maintaining consistency in product quality.					
We have seen a reduction in product defects since implementing digital twin technology.					
Digital twin technology has improved our ability to meet customer specifications and requirements.					
The integration of digital twin technology has improved the traceability of product components and processes.					
Overall, the use of digital twin technology has enhanced the product quality and consistency in our organisation.					

Here, the scoring was done as follows:

1 – Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, and 5 – Strongly Agree.

3.8 Data Collection Procedures

This study was relying on the primary data collection technique, in which the following approaches for data collecting can help to ensure complete and reliable information for the research on using digital twins to attain operational excellence:

- **Survey Framework:** A formal questionnaire was planned to obtain frequency data regards many aspects of the use of digital twins and the impact of such tools on operational improvements (Mendonça et al., 2022). Likert scale questions were used in the survey as it seeks to determine a number of aspects regarding digital twin and operation efficiency. In addition, demographic questions were also to be included in order to obtain background information from the participants.

- **Participant Enrolments:** The method of recruitment was entailing the use of a convenience sampling technique to collect the data from the respondents who are convenient to survey (Isaac, 2023). Besides the information on consent, confidentiality, and the aim of the research, e-mail invitations to complete the survey.
- **Data Security and Anonymity:** To address the issues of data security and confidentiality all the responses collected was coded and no one subject identification was made. The data to be stored in the servers are very secured to allow only the authorized persons from the research team to access them. Such privacy-protecting techniques, which aim at promoting truthful responses, will be familiar to the participants.
- **Data Validation and Cleansing:** After the survey session has been completed, the obtained data was checked and cleaned to eliminate any inconsistency and incompleteness. Next, analysis of answers to the consistency problems, missing numbers, and other suspicious values was done. Such responses assigned as invalid or partial were taken into consideration for the analysis.

Adhering to these accepted procedures of data collection assists the study to get strong and credible data thus enhancing the understanding of the role of Digital Twins in attaining operational effectiveness across so many sectors.

3.9 Data Analysis

To utilize SPSS Statistics, sometimes referred to as Statistical Packages for Social Sciences, a statistical analysis software program, to examine the data gathered on utilising digital twins for operational excellence. Originally created by SPSS Inc., IBM purchased it in 2009 (Nagaiah & Ayyanar, 2016). Through this, below given statistics were used to analyze the data:

- **Descriptive Statistics:** It provided a comprehensive picture of the key elements affecting the operational performance and Digital Twin implementation (Shi & Conrad, 2009). Calculated metrics comprising mean, standard deviation, will assist one in grasping the central tendency, variability, and response distribution over several sector (Rendón-Macías et al., 2016). This survey will present a clear image of how effectively participants perceive Digital Twins to be able to improve operational procedures to be effective and difficult.
- **Correlation analysis:** It looks at links between the variables to test the hypotheses. Determining whether elements are positively or negatively connected requires an analysis of Pearson's correlation coefficients or Spearman's rank-order correlations (Janse et al., 2021). Correlations might reveal, for instance, that higher degrees of Digital Twin integration match improved operational efficiency across specific sectors (Tao, Qi, et al., 2019).
- **Ordinal Regression**: In this instance, it was used to further investigate the variables influencing the Digital Twin's operational excellence results. The degree of change in the selected category-independent variables was ascertained using this statistical technique. The investigation enabled one to find out which of the factors have the most influence on the favourable outcomes, and if at all, these relationships are a function of the industry of business or the organisational posture (Tutz, 2022).

These analytical instruments put together offered a profound comprehension of how Digital Twins are used for operational efficiency in various industries and organisational contexts. The results not only shed light on opportunities and risks as well as provide valuable recommendations for those businesses that face the issues related to the enhancement of their ordinal operations using contemporary digital technologies including Digital Twins. Thus, the whole of this research intends to bring empirical facts to this field as a reference for strategic decisions and to encourage the innovation of operational management approaches.

3.10 Research Design Limitations

It is crucial to stress specific limitations related to the operational excellence digital applications entail. The major research design limitations are as follows:

1. **Sample Size and Generalizability:** The study is based on a sample of 300 respondents, which would be enough to make some statistical analysis but not fully capture the diversity and intricacies of all industries that employ digital twins. As such the findings may not reflect the whole sectors or geographies.
2. **Convenience Sampling Bias:** Nonetheless, there might still be an aspect of convenience sampling that leads to bias. A good representation of professionals in Digital Twins amongst the broader population may not be achieved because accessible participants who are willing to respond might represent just a fraction.
3. **Self-Reported Data:** The survey-based research depends on self-reported data, which can be influenced by participants' subjective perceptions, memory recall, and social desirability bias thereby compromising its authenticity and dependability.
4. **Cross-Sectional Design:** This research follows a cross-sectional design which means it only acquires information at one period in time, thereby limiting the ability to ascertain causative effects between Digital Twins adoption on operational excellence. Longitudinal studies would have been important for observing changes as well as causality over time between the adoption of Digital Twins and operational excellence.

3.11 Conclusion

The study aimed at investigating the possibility of implementing the concept of DT in engineering and manufacturing processes to improve operations. With increasing market pressures, environmental constraints, and competition, DTs pose the only solution to the current and futuristic organisational pressures through the emulation of accurate real-world systems for observation, diagnostics and enhancement. It included evaluating DT's economic viability, revenue generation capacity, effectiveness in enhancing relevant indicators, and potential solutions for increasing efficiency and minimizing costs. The research involved the use of a questionnaire that was developed to assess the level of awareness among the professionals involved; the questionnaire given had a 5-point Likert scale. Descriptive statistics, correlation, and ordinal regression analysis suggested that DT has a positive and practical potential for altering operations and increasing quality and efficiency in spite of some drawbacks such as high implementing costs and skills required.

Overall, the use of DT technology has much to benefit the operational execution in terms of overall performance. More studies will be required to establish the limit of DT technology utilization and consider factors that may hinder the implementation process as well as come up with worthy suggestions on the effectiveness of DT technology in dealing with competitiveness challenges.

CHAPTER IV:

RESULTS AND INTERPRETATION

4.1 Reliability

Table 2 - Reliability statistics

Cronbach's Alpha	N of Items
.954	45

The scale's 45 items have great internal consistency, as shown by Cronbach's Alpha score of 0.954 in Table 2 above. This suggests that the items measure same underlying concept and are strongly associated. A number above 0.9 is usually regarded as excellent since it indicates strong reliability and guarantees that the scale is reliable for evaluating the desired construct.

4.2 Frequency Table

Table 3 - Demographics

Category	Data Fields	Frequency	Percent
Please mention your gender	Male	189	59.4
	Female	129	40.6
To which age group do you belong	18-24 Years	101	31.8
	25-34 Years	98	30.8
	35-44 Years	82	25.8
	45-54 Years	22	6.9
	55-64 Years	8	2.5
	65 Years and above	7	2.2
Please mention your Education Level	High school or equivalent	13	4.1
	Bachelor's degree	98	30.8
	Master's degree	162	50.9

	Doctorate or advanced professional degree	29	9.1
	Other	16	5
Employment Status	Employed full-time	228	71.7
	Employed part-time	50	15.7
	Self-employed	26	8.2
	Retired	4	1.3
	Other	10	3.1
How many total years of work experience do you have?	< 5 Years	140	44
	5-10 Years	96	30.2
	10-15 Years	47	14.8
	15-20 years	19	6
	20-25 Years	14	4.4
	>25 Years	2	0.6
What is your annual income (in INR)	Below 1,50,000	97	30.5
	1,50,000 - 2,99,999	79	24.8
	3,00,000 - 4,49,999	79	24.8
	4,50,000 - 5,99,999	31	9.7
	6,00,000 - 9,99,999	14	4.4
	10,00,000 or more	10	3.1
	Prefer not to say.	8	2.5
Type of industry you are working in	Aerospace and Defence	24	7.5
	Automotive	21	6.6
	Chemical & Paints	29	9.1
	Paper & Textile	27	8.5
	Energy & Utilities	22	6.9

	FMCG	17	5.3
	Information Technology (Technology services, Software & Hardware)	122	38.4
	Pharma Manufacturing & Services	20	6.3
	Mining & Metal production	8	2.5
	Oil & gas	5	1.6
	Others	23	7.2
What is the size of your organisation with respect to number of employees?	Small (<100)	120	37.7
	Medium (100-1000)	154	48.4
	Large (1000-5000)	34	10.7
	Enterprise (>5000)	10	3.1

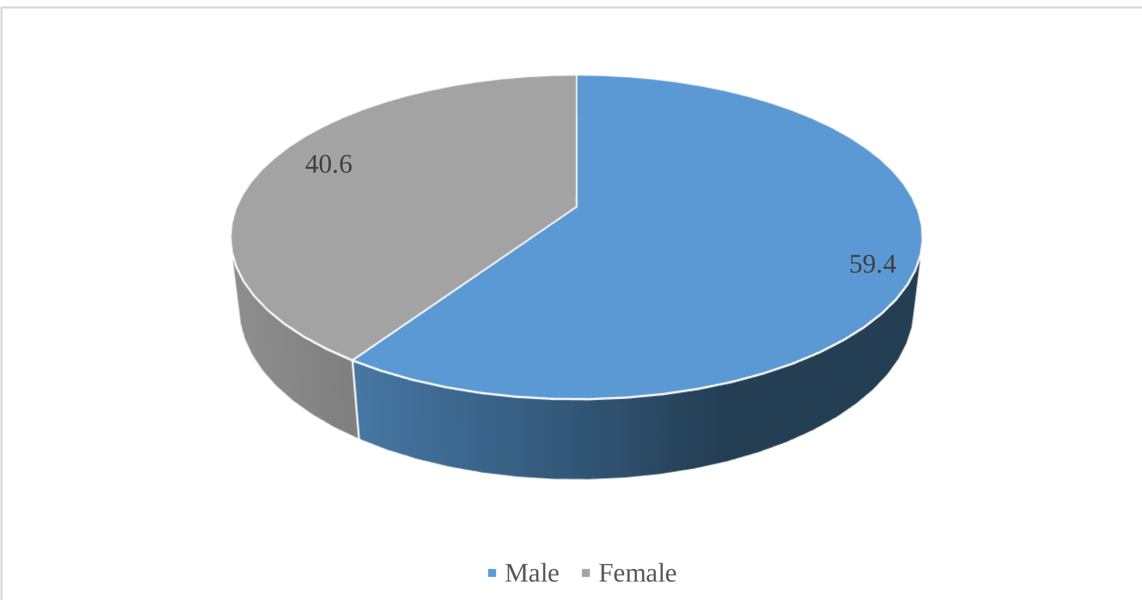

Figure 18: Gender

The gender distribution of the sample is shown in Figure 18 above. 189 (59.4%) of the respondents are male, and (40.6%) are male, suggesting that there are more men than women in the sample.

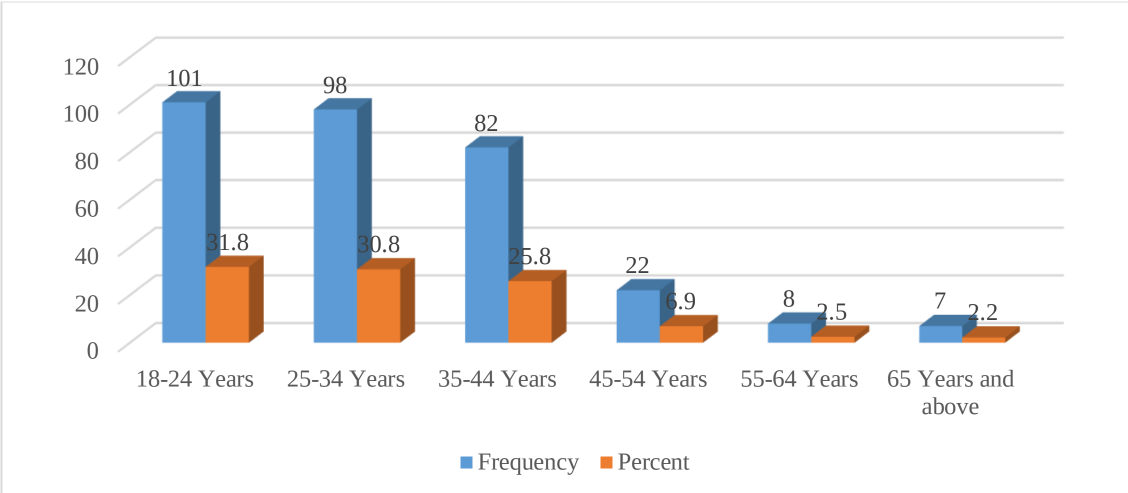

Figure 19: To which age group do you belong

The respondents' age distribution is displayed in Figure 19 above. 31.8% of the participants are between the ages of 18-24; 98 (30.8%) are between the ages of 25-34; 25.7% are between the ages of 35 and 44; 6.9% are between the ages of 45-54; 2.5% are between the ages of 55-64; and 2.2% are 65 years of age or more.

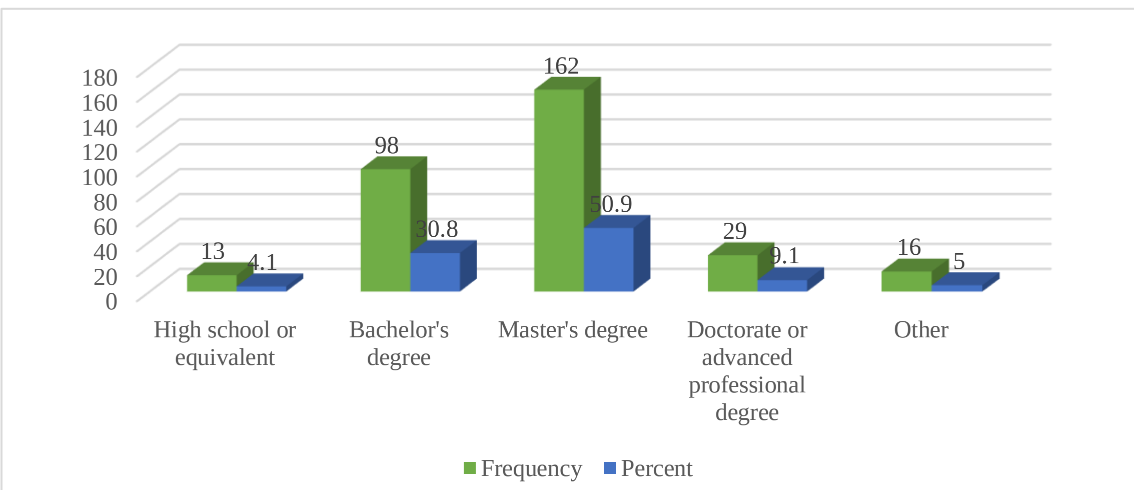

Figure 20: Please mention your Education Level

The respondents' educational attainment is displayed in Figure 20 above. 13 (4.1%) have completed high school or its equivalent, (30.8%) have earned a bachelor's degree, (50.9%) have earned a master's degree, (9.1%) have earned a doctorate or advanced professional degree, and (5.0%) fell into the "other" division.

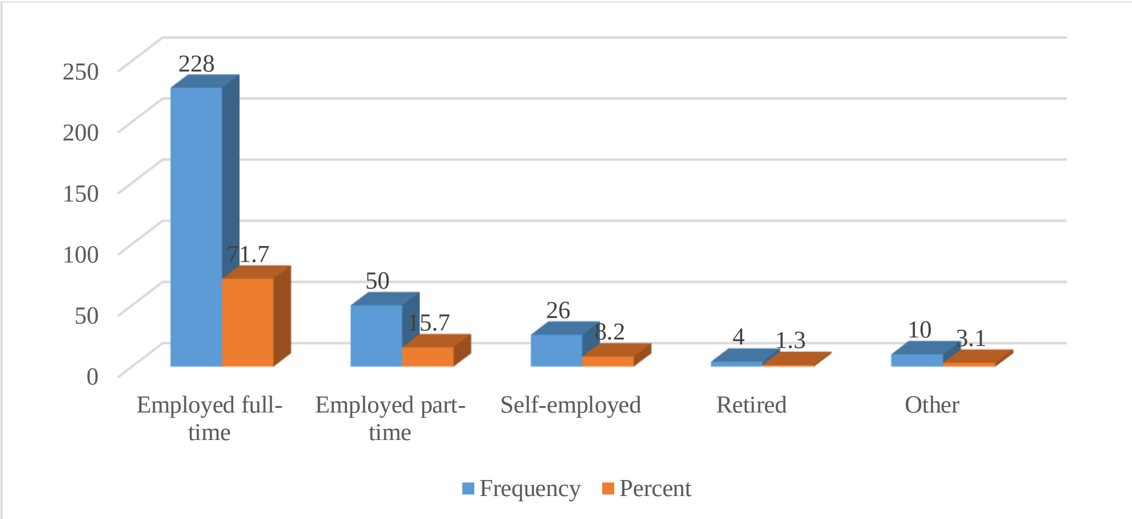

Figure 21: Employment Status

The respondent's employment status is organised in Figure 21 above. There are (71.7%) full-time employees, (15.7%) part-time employees, (8.2%) independent contractors, (1.3%) retirees, and (3.1%) in the "other" group.

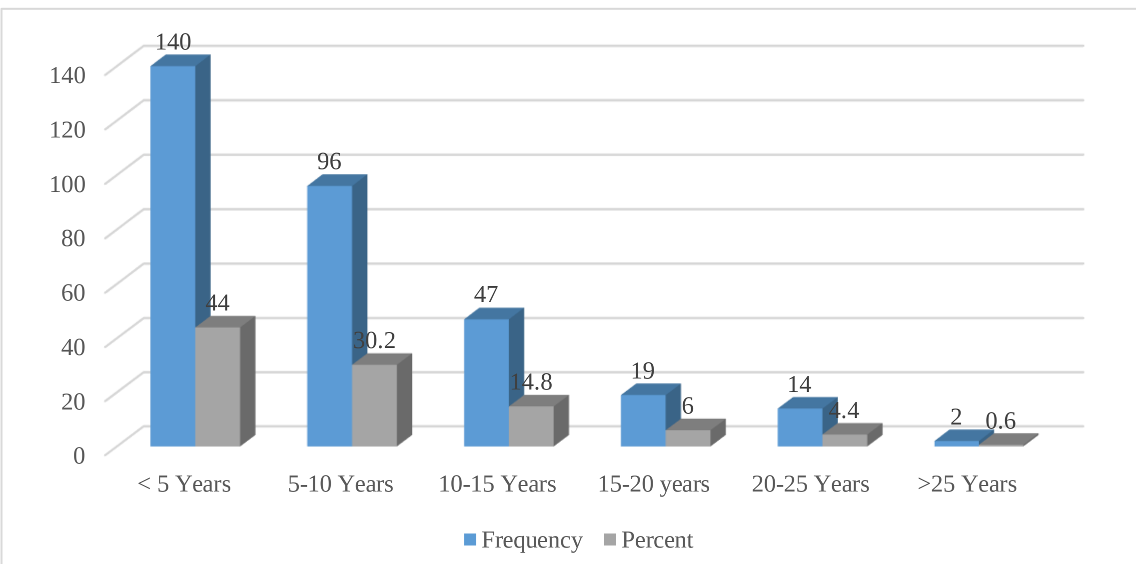

Figure 22: How many total years of work experience do you have?

The model's goodness-of-fit statistics are shown in figure 22 above. With eight df, the Pearson Chi-Square value is 149.851, and the Deviance, with 8 df, is 33.202. The model matches the data well, as evidenced by the significance level .000 for both tests.

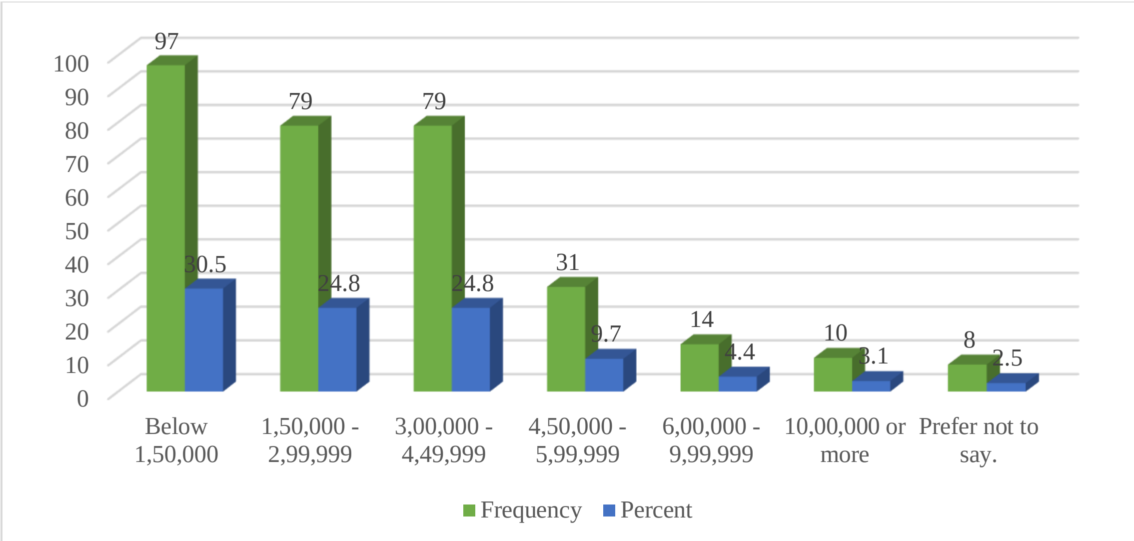

Figure 23: What is your annual income (in INR)

The above Figure 23 presents the annual income distribution of respondents (in INR). Of the participants, (30.5%) earn below ₹1,50,000, (24.8%) fall in the ₹1,50,000 - ₹2,99,999 range and another (24.8%) earn between ₹3,00,000 - ₹4,49,999. Additionally, (9.7%) have an income of ₹4,50,000 - ₹5,99,999, 4 (4.4%) fall in the ₹6,00,000 - ₹9,99,999 range, and 10 (3.1%) report earning ₹10,00,000 or more. Lastly, (2.5%) preferred not to disclose their income. The data reveals that the majority of respondents earn below ₹4,49,999.

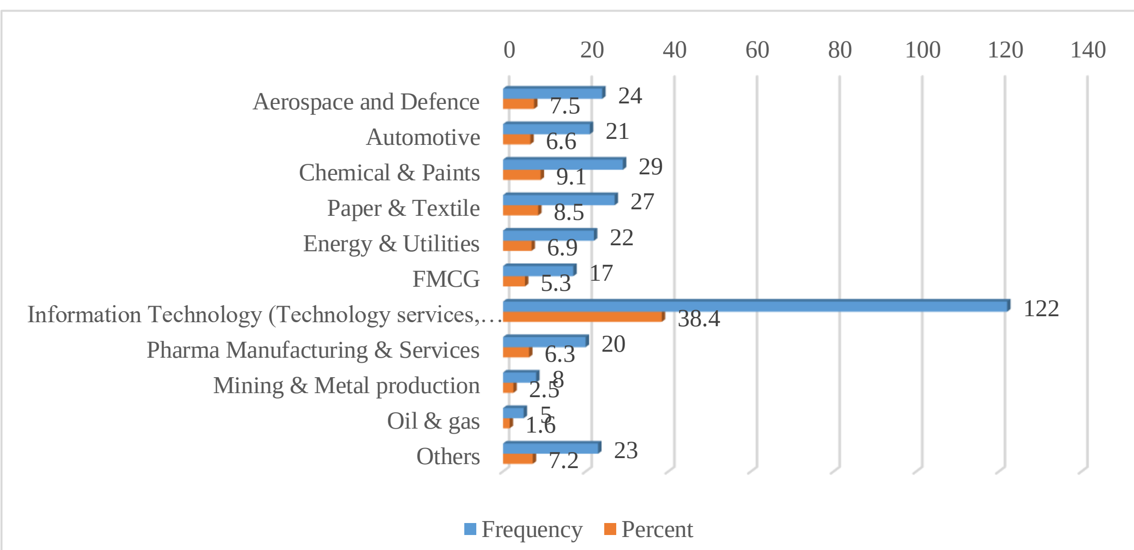

Figure 24: Type of industry you are working in

According to the industry they work in is shown in Figure 24 above. 7.5% of the participants work in the aerospace and defence industry, 6.6% in the automotive, 9.1% in the chemical and paints, 8.5% in the paper and textile, and 6.9% in the energy and utilities. The FMCG sector makeup 5.3% of the employees, whereas the largest group, information technology, which includes hardware, software, and services, employs 38.4%. Furthermore, 6.3% work in pharmaceutical manufacturing and services, 2.5 % mine and produce metals, 1.6 % work in oil and gas, and 7.2 % work in other industries.

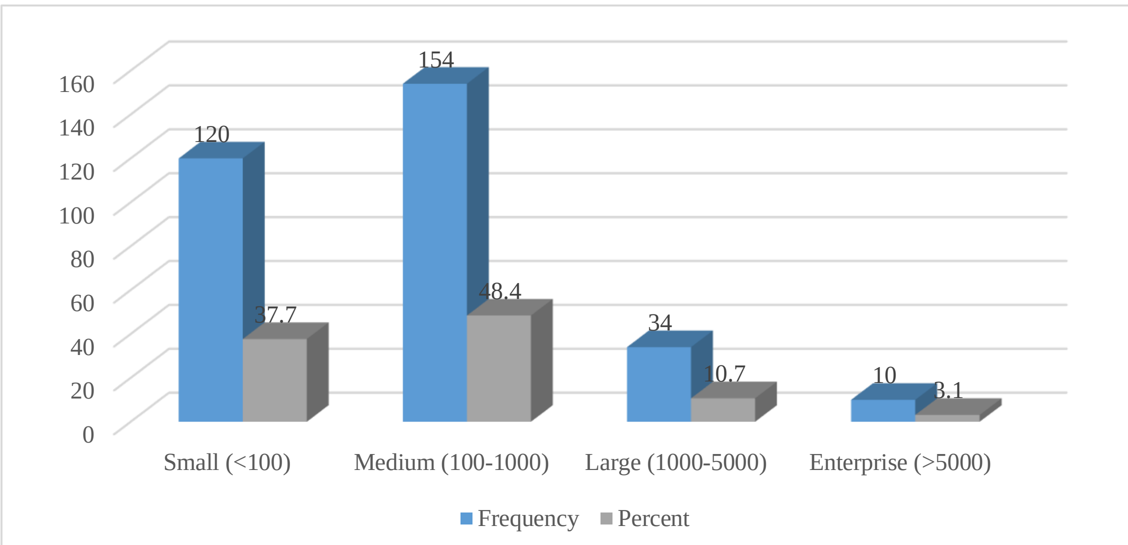

Figure 25: Organisation Size

The distribution of respondents by the size of their company concerning the number of employees is depicted in Figure 25 above. Of the participants, (37.7%) are employed by small businesses with fewer than 100 workers, and (48.4%) are employed by medium-sized businesses with 100–1,000 workers. Furthermore, 10 respondents (3.1%) are employed by companies with more than 5,000 employees, and (10.7%) are employed by large organizations with 1,000–5,000 people.

Table 4 – Adoption of Digital Twin Technology

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Digital twin technology is essential for enhancing operational efficiency in organization.	Frequency	23	67	49	151	28
	Percent	7.2	21.1	15.4	47.5	8.8
The use of digital twin technology has increased collaboration among different departments in organization.	Frequency	5	66	55	122	70
	Percent	1.6	20.8	17.3	38.4	22
We have encountered challenges in integrating digital twin technology with existing systems in our organization.	Frequency	12	55	66	133	52
	Percent	3.8	17.3	20.8	41.8	16.4
The adoption of digital twin technology has improved our organization's decision-making process.	Frequency	13	50	55	110	90
	Percent	4.1	15.7	17.3	34.6	28.3
Training and upskilling employees for the use of digital twin technology has been effective.	Frequency	15	55	65	115	68
	Percent	4.7	17.3	20.4	36.2	21.4

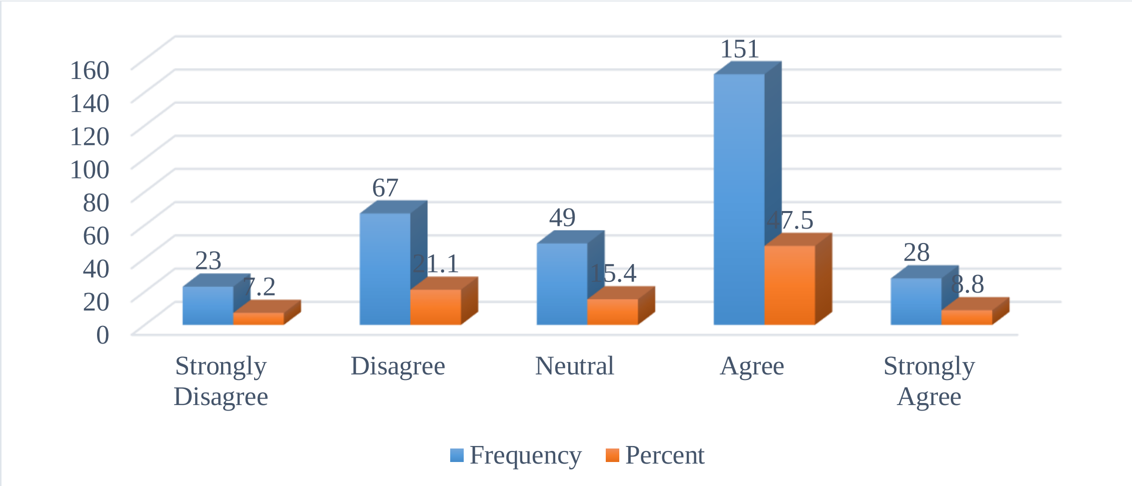

Figure 26: Digital Twin Technology Boosts Organizational Efficiency

The opinions of respondents regarding the significance of digital twin technology to enhancing operational efficiency in their organisation in Figure 26 above. Of the participants, (21.1%) disagree with this statement, and (7.2%) strongly disagree. respondents, or 15.4% of the sample, have no opinion. On the other hand, (8.8%) strongly agree and (47.5%) believe that digital twin technology is necessary.

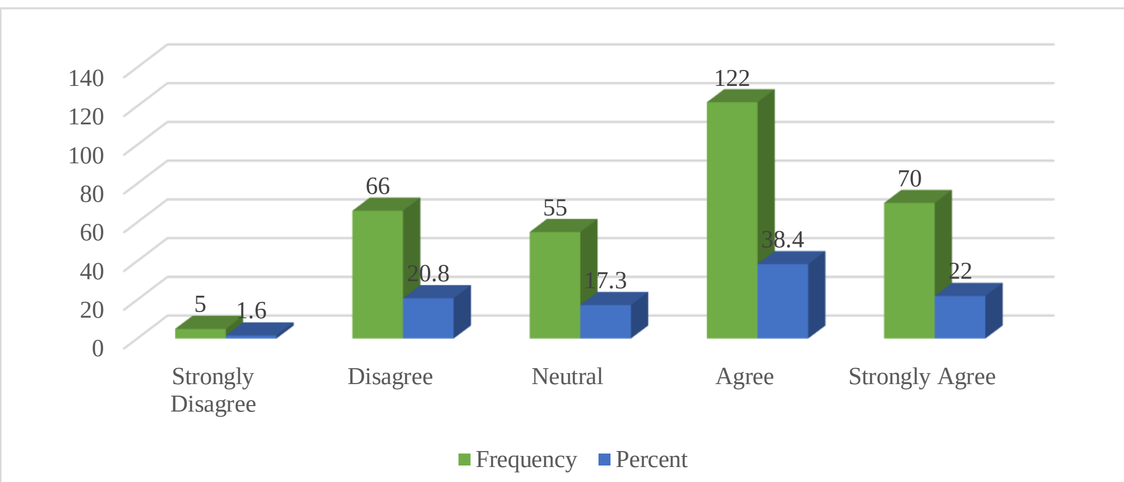

Figure 27: Digital twin technology enhances cross-departmental collaboration.

The respondents' views on whether the utilization of digital twin technology has increased collaboration among different departments in their organization in Figure 27 above. Of the participants, 20.8% disagree with the statement, and 1.6% strongly disagree. Respondents adopt a neutral position (17.3%). Positively, respondents agree (38.4%) and strongly agree (22.0%) that the use of digital twin technology has improved departmental teamwork.

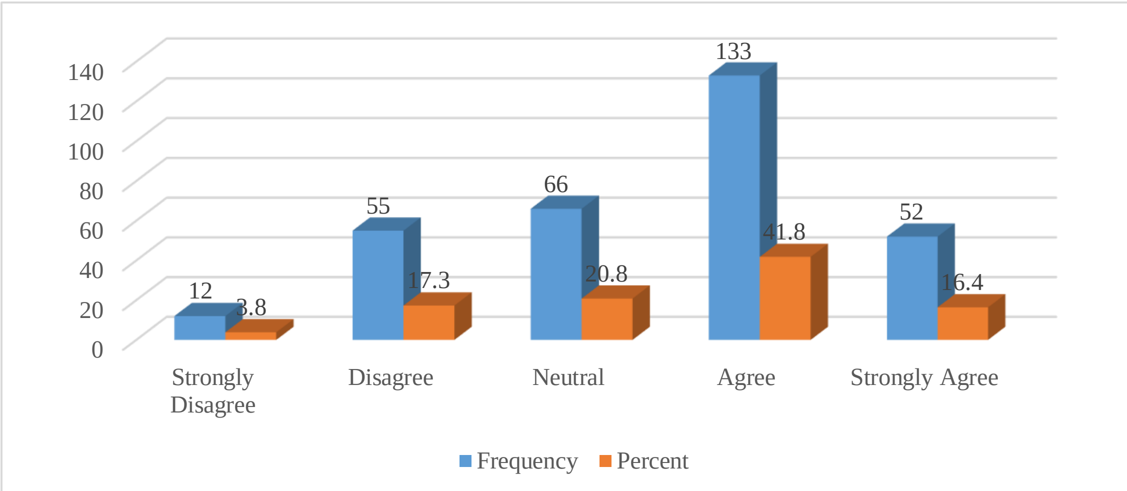

Figure 28: Digital twin integration faces challenges.

The experiences with the difficulties of integrating digital twin technology with their organization's current systems are depicted in Figure 28 above. Of the participants, (17.3%) disagree and (3.8%) strongly disagree that they have faced such difficulties. respondents (20.8%) have a neutral stance. (41.8%) of the respondents, on the other hand, agree that there are obstacles, and 52 (16.4%) strongly agree.

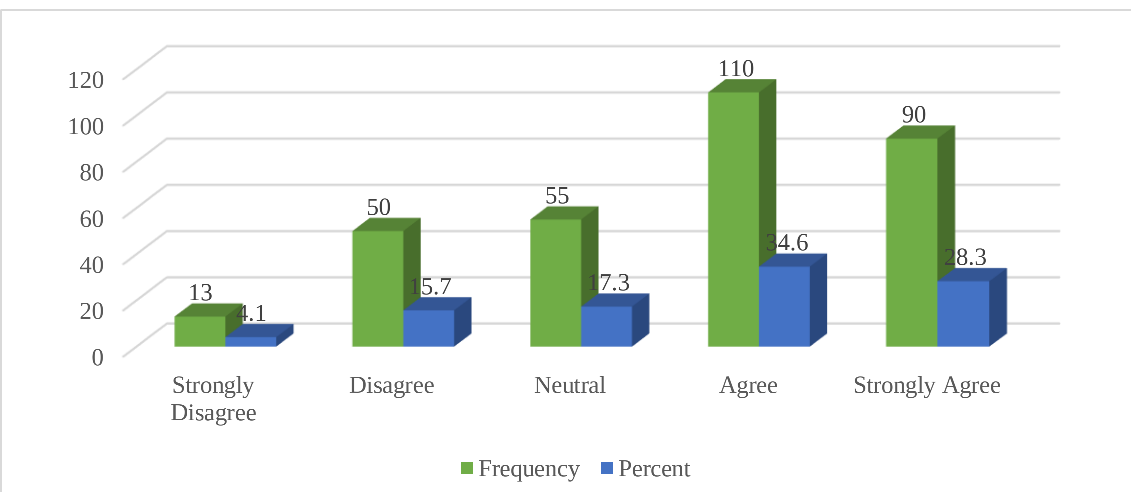

Figure 29: Digital twin adoption enhances decision-making.

The respondents' opinions regarding whether the use of digital twin technology has enhanced their organization's decision-making process in Figure 29 above. Of the participants, (15.7%) disagree with the statement, while (4.1%) strongly disagree. respondents (17.3%) adopt a neutral stance. On the other hand, a sizable portion of respondents have a favourable opinion, with (28.3%) strongly agreeing and (34.6%) agreeing that digital twin technology has improved their ability to make decisions.

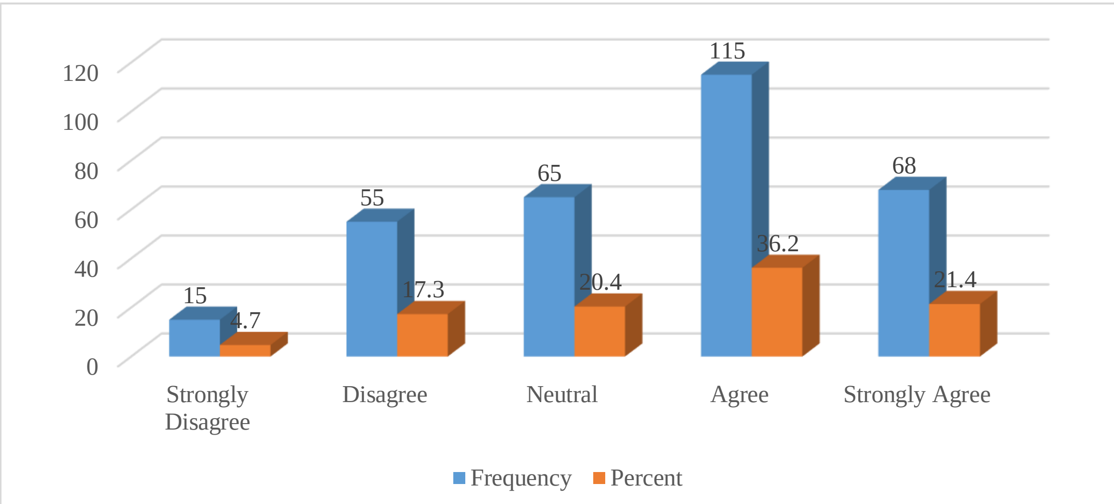

Figure 30: Employee training for digital twin technology is effective.

The responses about how well employees are trained and upskilled to use digital twin technology are shown in Figure 30 above. Of the participants, (17.3%) disagree and (4.7%) strongly disagree that such training is effective. 20.4% of respondents have a neutral position. Positively, respondents (21.4%) highly agree, and respondents (36.2%) agree that the training has been effective.

Table 5 – Financial Viability

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Digital twin adoption is detrimental to our organization's financial viability.	Frequency	27	81	35	126	49
	Percent	8.5	25.5	11	39.6	15.4
I believe that adopting digital twins can have a positive impact on our organization's financial health.	Frequency	11	48	54	137	68
	Percent	3.5	15.1	17	43.1	21.4
The financial benefits of implementing digital twins are questionable.	Frequency	11	55	75	120	57
	Percent	3.5	17.3	23.6	37.7	17.9
Digital twins are likely to yield a favourable Return on Investment (ROI) for our organization.	Frequency	15	51	47	131	74
	Percent	4.7	16	14.8	41.2	23.3
I am confident that digital twin adoption will result in economic benefits for our organization.	Frequency	22	45	70	108	73
	Percent	6.9	14.2	22	34	23

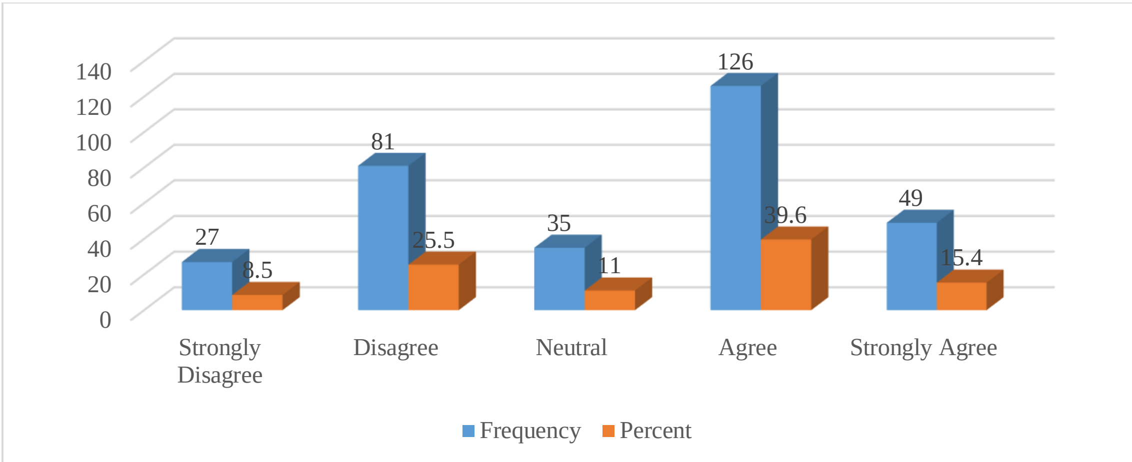

Figure 31: Digital twin adoption harms financial viability.

The implementation of digital twin technology is detrimental to their organization's financial viability (Figure 31 above). The claim that adopting a digital twin has a detrimental effect on financial health is one that (25.5%) and (8.5%) of the participants disagree with. Respondents (11.0%) had a neutral position. In contrast, (15.4%) of respondents strongly agree and (39.6%) agree that there are financial obstacles to adopting digital twin technology.

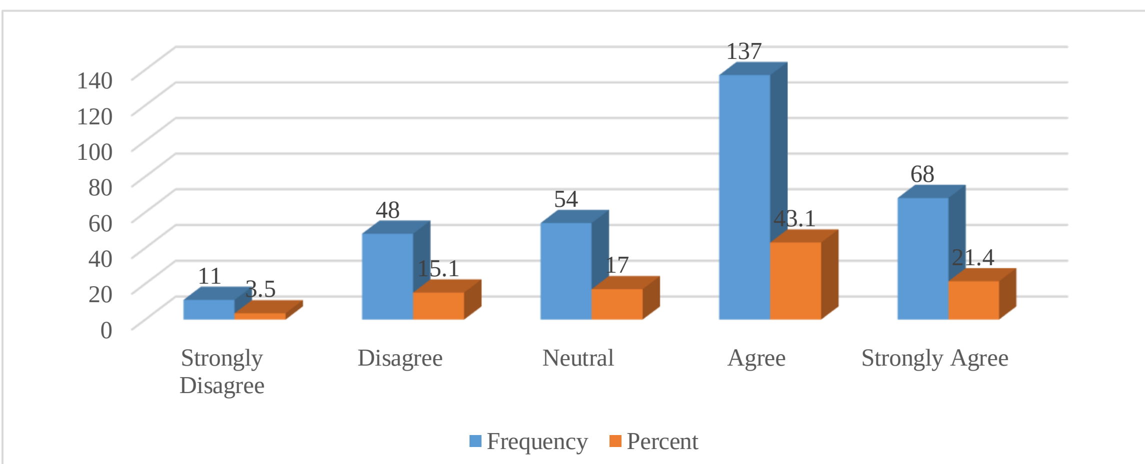

Figure 32: Digital twin adoption boosts financial health.

The opinions regarding the positive financial influences of adopting digital twin technology are shown in Figure 32 above. Of the participants, (15.1%) disagree with the statement, and (3.5%) strongly disagree. respondents (17.0%) have a neutral view. On the plus side, (21.4%) of respondents strongly agree and (43.1%) agree that implementing digital twins can improve the financial health of their company.

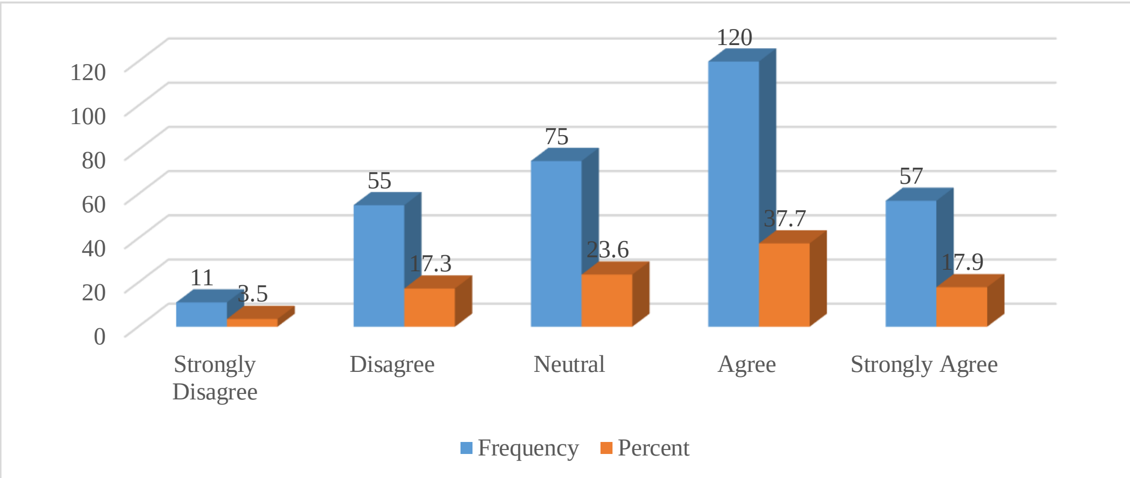

Figure 33: The financial benefits of implementing digital twins are questionable.

The above Figure 33 presents respondents' views on the statement that the financial benefits of implementing digital twins are questionable. Among the participants, 11 (3.5%) strongly disagree, and 55 (17.3%) disagree. Meanwhile, 75 respondents (23.6%) are neutral on the issue. In contrast, a significant number of express doubts, with 120 (37.7%) agreeing and 57 (17.9%) strongly agreeing that the financial advantages of digital twins are uncertain.

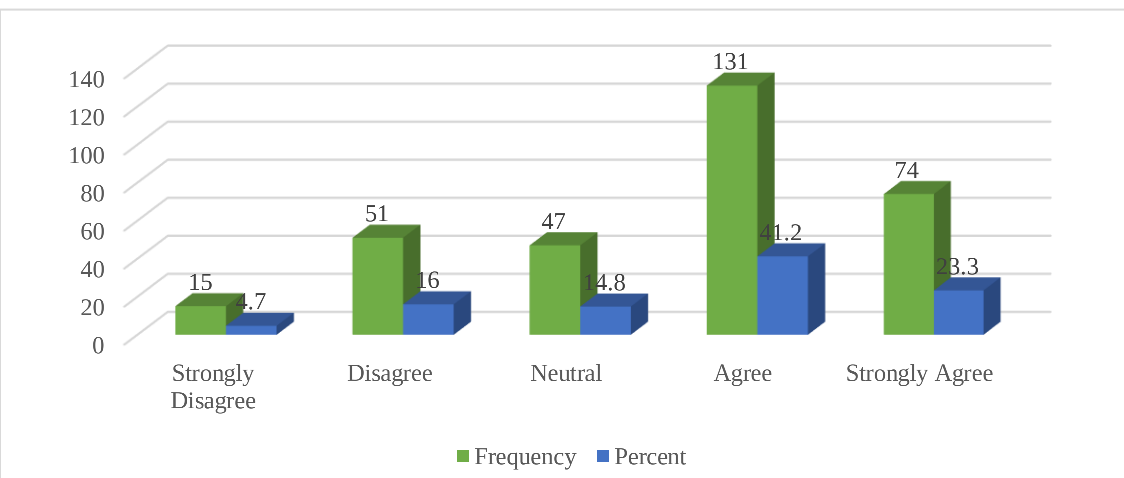

Figure 34: Digital twins promise a favorable ROI.

The digital twins are likely to yield a favourable Return on Investment (ROI) for their organisation are shown in Figure 34 above. Of the participants, (16.0%) disagree with this assertion, and (4.7%) strongly disagree. There are (14.8%) that have a neutral opinion. On the other hand, (23.3%) of respondents strongly agree and (41.2%) respondents agree that digital twins should yield a positive return on investment.

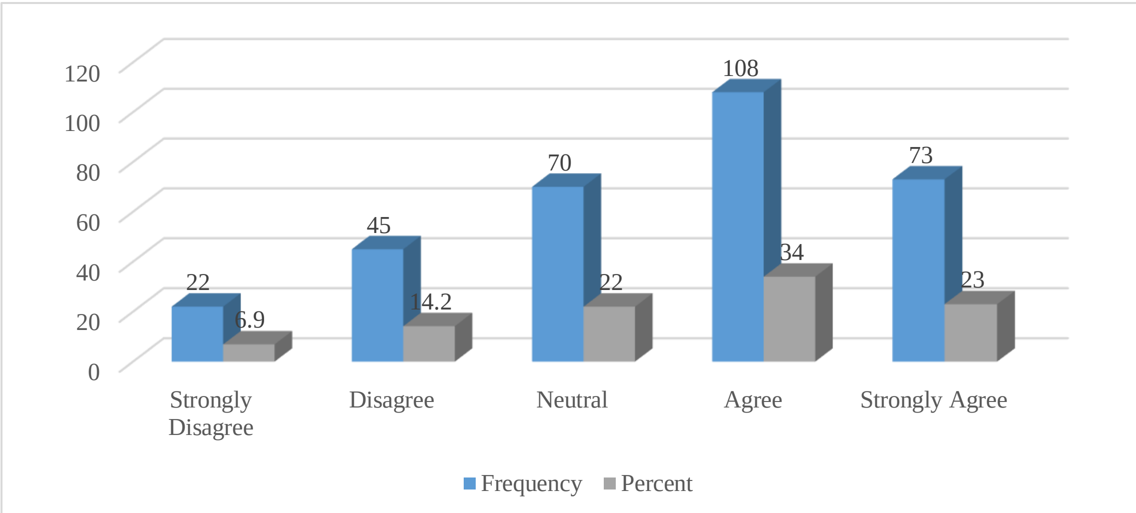

Figure 35: Digital twin adoption ensures economic benefits.

The confidence in the economic benefits of adopting digital twins for their organisation is seen in Figure 35 above. Of the participants, (14.2%) disagree with the statement, and (6.9%) strongly disagree. Respondents (22.0%) adopt a neutral position. The good news is that respondents (34.0%) agree and (23.0%) strongly believe that their company will profit from the use of digital twins.

Table 6 - Operational Excellence (Measured KPIs)

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Customer Satisfaction						
Adoption of Digital Twin will enable better anticipation of customer needs & preference, leading to personalised & tailored services.	Frequency	27	75	46	117	53
	Percent	8.5	23.6	14.5	36.8	16.7
I am confident that digital twin adoption will lead to improved customer satisfaction & loyalty for our organization.	Frequency	14	51	39	143	71
	Percent	4.4	16	12.3	45	22.3
Digital twins play a significant role in enhancing customer satisfaction in our organization.	Frequency	14	54	75	120	55
	Percent	4.4	17	23.6	37.7	17.3
Revenue Growth						
The adoption of digital twins positively affects our organization's revenue growth.	Frequency	14	62	57	111	74
	Percent	4.4	19.5	17.9	34.9	23.3
I am confident that implementing digital twins will lead to increased revenue growth for our organization.	Frequency	16	50	52	134	66
	Percent	5	15.7	16.4	42.1	20.8

Implementation of Digital Twin will enable better decision – making, strategic planning & leading to revenue growth.	Frequency	19	54	58	111	76
	Percent	6	17	18.2	34.9	23.9
Productivity: (monetary gain, resource optimisation, throughput, efficiency)						
Digital twins enhance productivity within our organization.	Frequency	20	57	58	120	63
	Percent	6.3	17.9	18.2	37.7	19.8
I am confident that digital twin adoption will streamline processes & workflow, leading to higher efficiency & output for our organization.	Frequency	17	61	52	124	64
	Percent	5.3	19.2	16.4	39	20.1
Digital twins significantly improve overall operational efficiency & productivity gains in our organization.	Frequency	16	53	65	123	61
	Percent	5	16.7	20.4	38.7	19.2
Quality Control						
Digital twins positively affect our organization's quality control efforts.	Frequency	24	64	42	106	82
	Percent	7.5	20.1	13.2	33.3	25.8
I am confident that implementing digital twins results in better quality control within our organization.	Frequency	13	62	63	119	61
	Percent	4.1	19.5	19.8	37.4	19.2

The adoption of digital twins leads to overall improvement in product or service quality standards in our organization.	Frequency	20	54	56	123	65
	Percent	6.3	17	17.6	38.7	20.4
Cost Efficiency						
Implementation of digital twins will optimise resource utilisation & reduce operational expenses.	Frequency	17	53	67	118	63
	Percent	5.3	16.7	21.1	37.1	19.8
I am confident that digital twin adoption will enable better forecasting & budgeting, leading to improved cost efficiency for our organization.	Frequency	24	61	43	116	74
	Percent	7.5	19.2	13.5	36.5	23.3
Digital twins significantly improve cost efficiency in our organization.	Frequency	23	59	59	106	71
	Percent	7.2	18.6	18.6	33.3	22.3

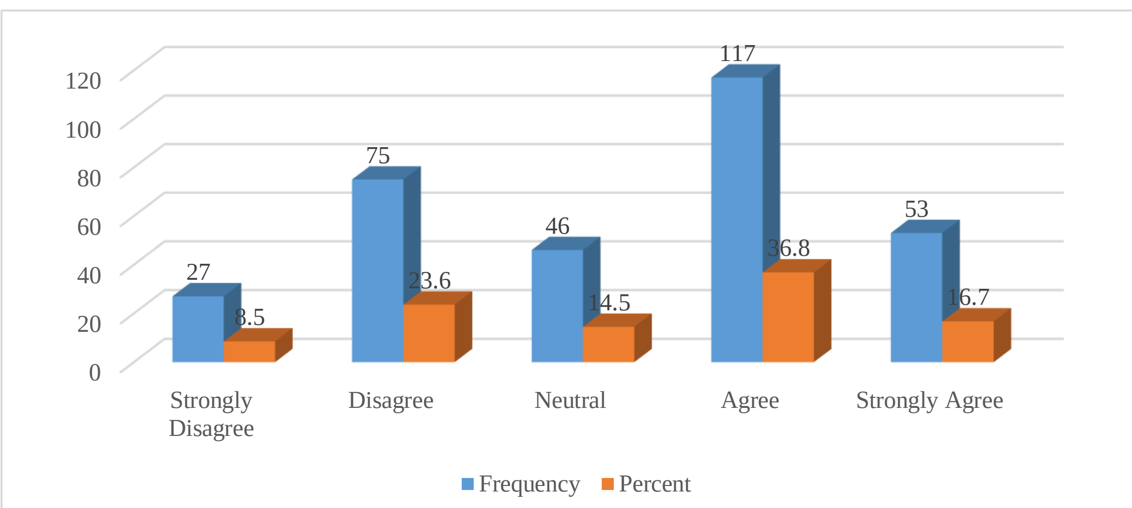

Figure 36: Digital twin adoption enhances customer personalization.

The adoption of digital twin technology will enhance the ability to anticipate client needs and preferences, enabling personalised and tailored services, are presented in Figure 36 above. Of the participants, (23.6%) disagree with this statement, and (8.5%) strongly disagree. The majority of respondents (1.5%) have a neutral position. On the other hand, 53 (16.7%) highly agree and 117 (36.8%) agree that the utilization of digital twins will enhance consumer anticipation and personalisation initiatives.

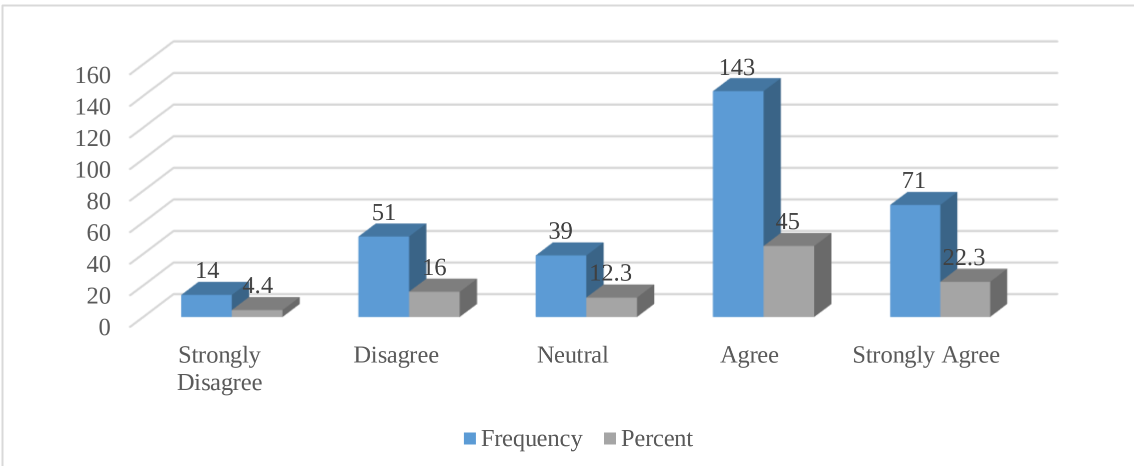

Figure 37: Digital twin adoption boosts customer satisfaction and loyalty.

The confidence in the potential of using digital twins to increase customer satisfaction and loyalty within their company is seen in Figure 37. Of the participants, (16.0%) disagree with the statement, and (4.4%) strongly disagree. whereas (12.3%) have a neutral position. Positively, a sizable percentage of respondents— (45.0%) agree and (22.3%) strongly agree—think that the adoption of digital twins will boost consumer happiness and loyalty.

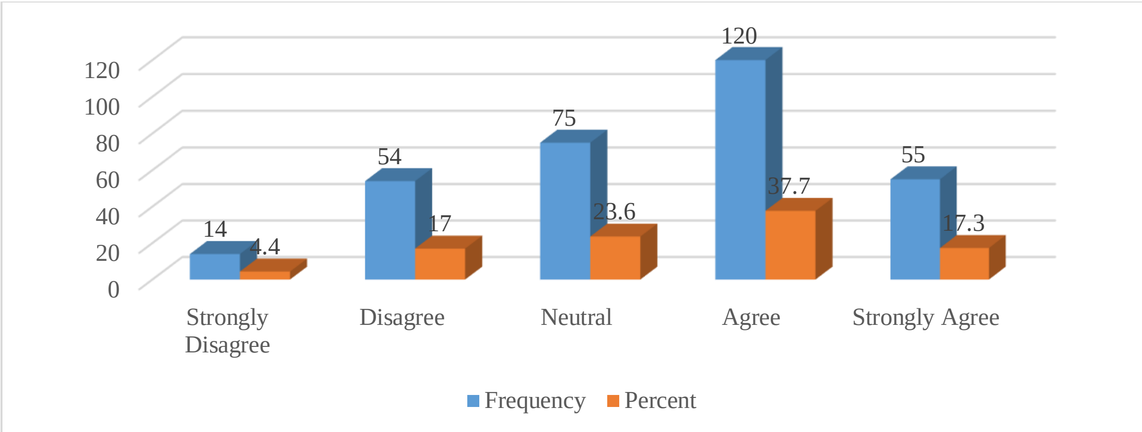

Figure 38: Digital twins enhance customer satisfaction.

The figure above 38 Respondents' opinions about how digital twins are enhancing customer satisfaction with their organisation. Of the respondents, (17.0%) disagree and (4.4%) strongly disagree that digital twins have a major impact on consumer satisfaction. Meanwhile (23.6%) adopt a neutral position. On the other hand, (17.3%) strongly agree and (37.7%) believe that digital twins have a good effect on consumer satisfaction.

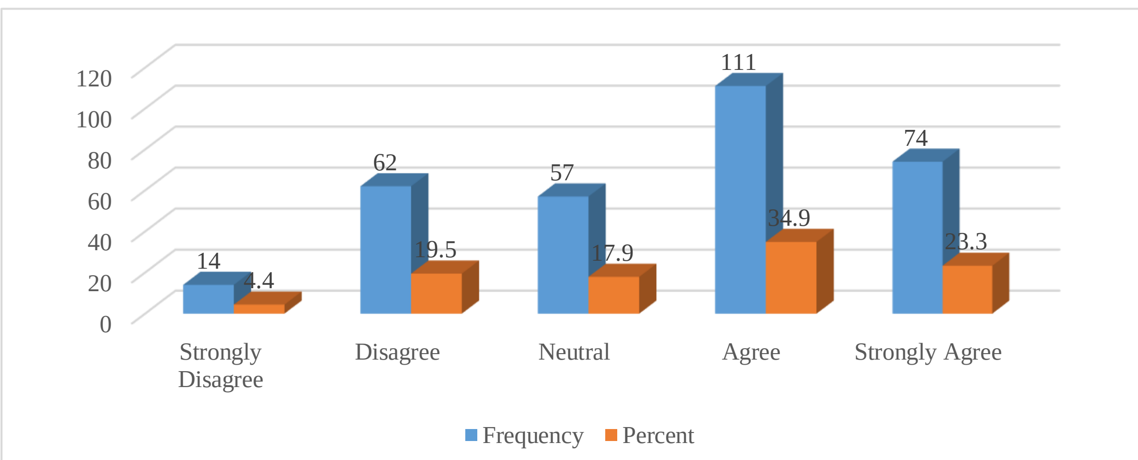

Figure 39: Digital twin adoption drives revenue growth.

The impact of adopting digital twins on the organization's revenue growth is shown in Figure 39 above. Of the participants, 19.5% disagree and 4.4% strongly disagree that revenue growth is positively impacted by digital twins. Respondents have a neutral position

(17.9%). Positively, 23.3% strongly agree and 34.9% believe that revenue growth is facilitated by digital twin technology.

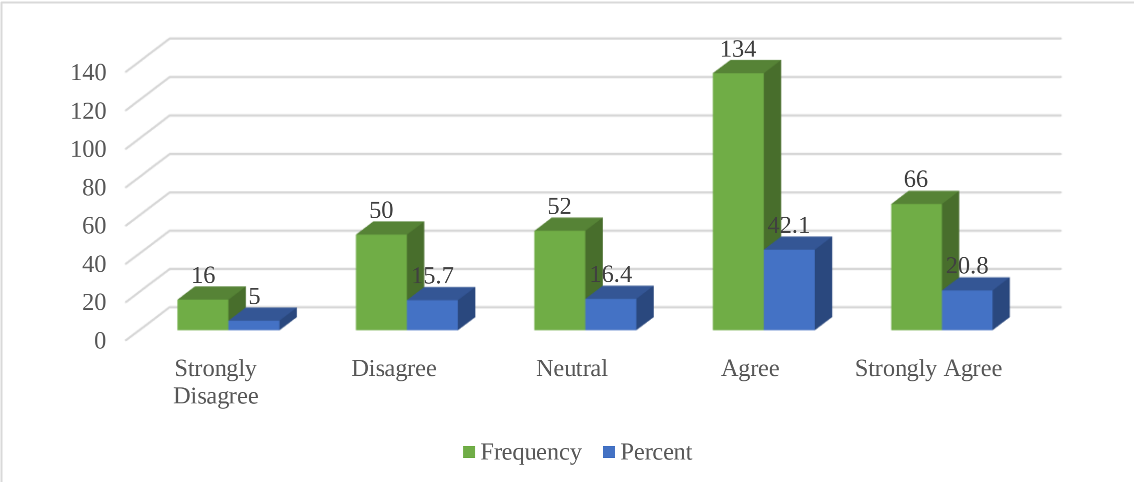

Figure 40: Digital twin implementation boosts revenue growth.

The above Figure 40 shows' confidence in potential of digital twin implementation to drive revenue growth for their organization. Among the participants, (5.0%) strongly disagree, and (15.7%) disagree with this potential. A neutral position is held by (16.4%). On the positive side, a significant number, of respondents (42.1%), agree, and (20.8%) strongly agree that digital twins will enhance revenue growth.

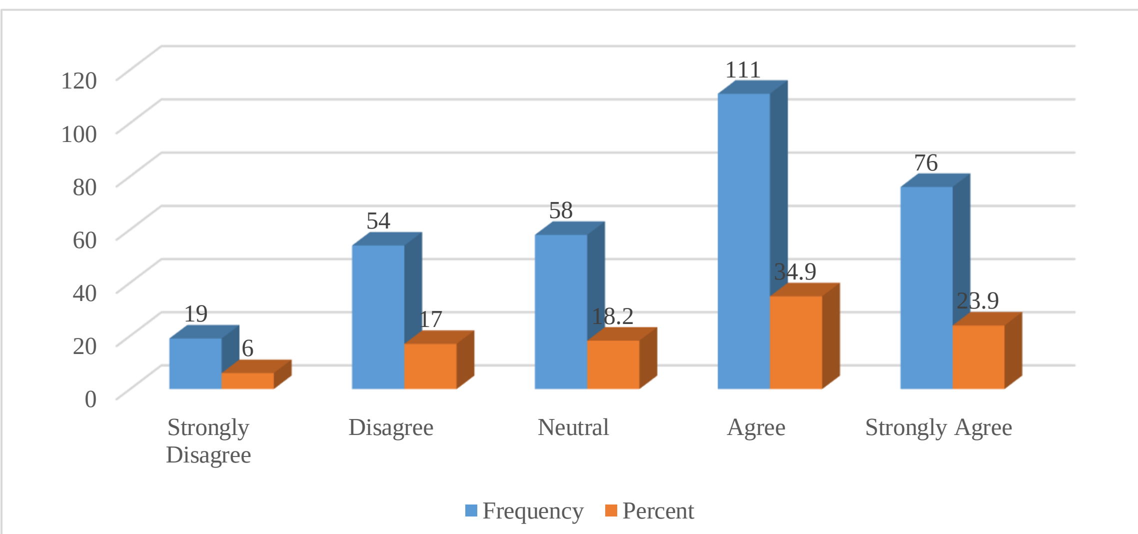

Figure 41: Digital twins boost revenue growth.

The digital twin technology will enhance decision-making and strategic planning and ultimately end in greater revenue are shown in Figure 41 above. Of the participants, 17.0% disagree with this statement, and 6.0% strongly disagree. Respondents have a neutral position (18.2%). On the other hand, most respondents have a favourable view, with 34.9% agreeing and 23.9% strongly agreeing that digital twins help with better strategic planning and decision-making, which can lead to more income.

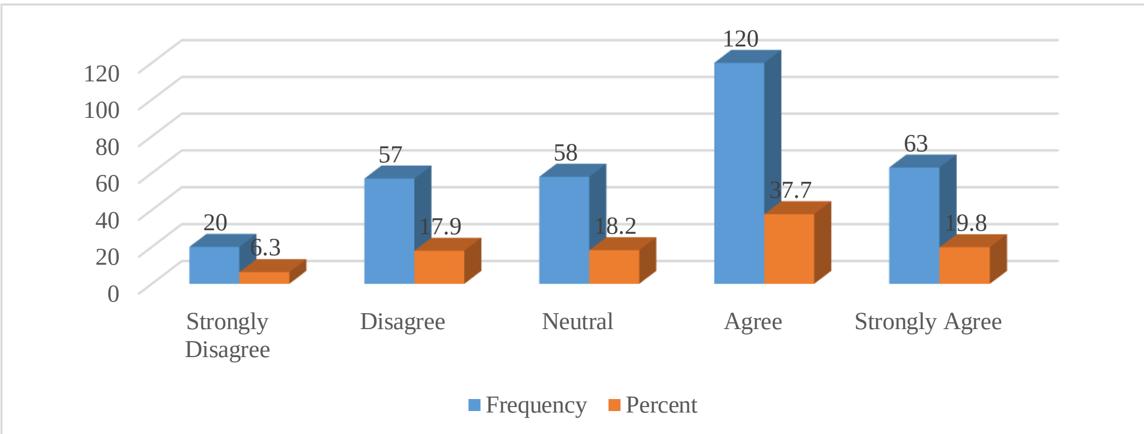

Figure 42: Digital twins enhance productivity within our organization.

The effect of digital twins enhance productivity with their organization is shown in Figure 42 above. Of the participants, 17.9% disagree and 6.3% strongly disagree that digital twins increase productivity. Of the responders, (18.2%) had a neutral stance. Positively, respondents agree that digital twins boost productivity (37.7%) and strongly agree (19.8%).

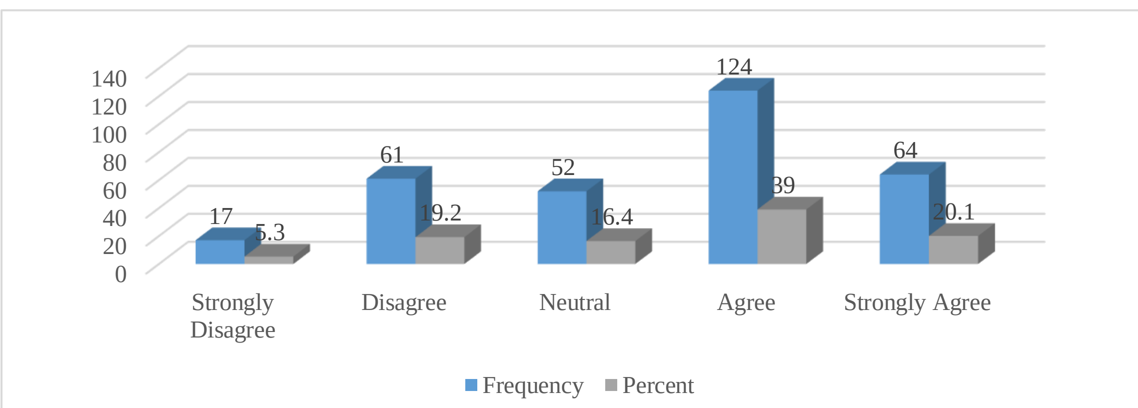

Figure 43: Digital twin adoption boosts efficiency and output.

The data of confidence that the adoption of digital twins will optimise workflows and processes, leading to increased productivity and efficiency for their organisation, is shown in Figure 43 above. Of the participants, 19.2% disagree with this assertion, and 5.3% strongly disagree. Respondents adopt a neutral position (16.4%). On the plus side, respondents strongly agree (20.1%) and agree (39.0%) that digital twins will increase productivity and efficiency.

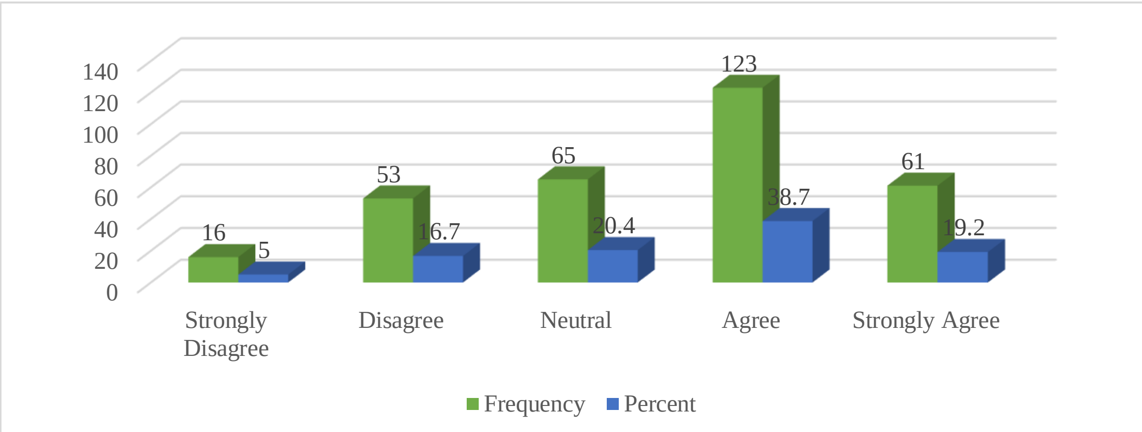

Figure 44: Digital twins enhance efficiency and productivity.

The distribution of opinions about how digital twins affect an organization's overall operational efficiency and productivity improvements is shown in Figure 44 above. Of the participants, (16.7%) disagree with the statement, and (5.0%) strongly disagree. Respondents (20.4%) have a neutral view. Positively, respondents (19.2%) strongly agree and (38.7%) believe that digital twins greatly increase productivity and operational efficiency.

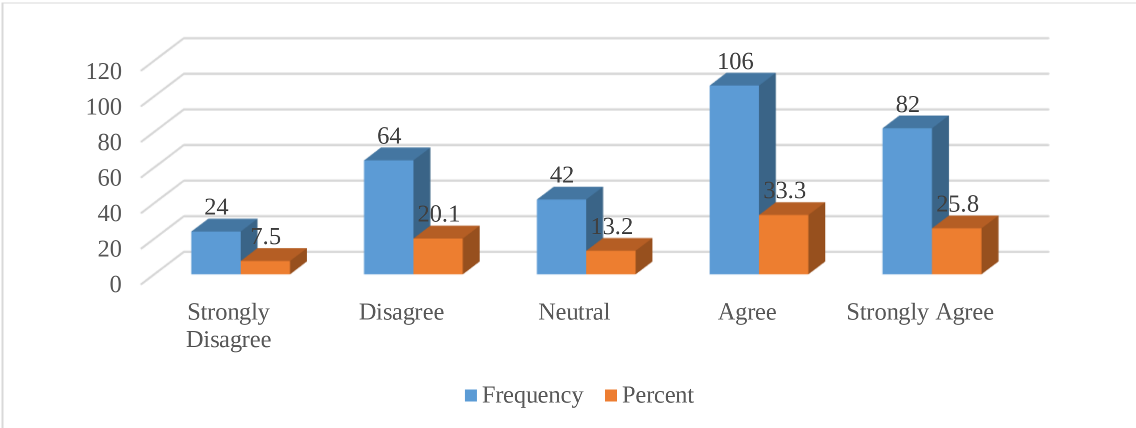

Figure 45: Digital twins positively affect our organization's quality control efforts.

The above Figure 45 shows the impact of digital twins on quality control efforts within the organization. Of the 318 respondents, 33.3% agreed and 25.8% strongly agreed that digital twins positively affect quality control, while 13.2% remained neutral. However, 20.1% disagreed, and 7.5% strongly disagreed, indicating some reservations among a portion of respondents.

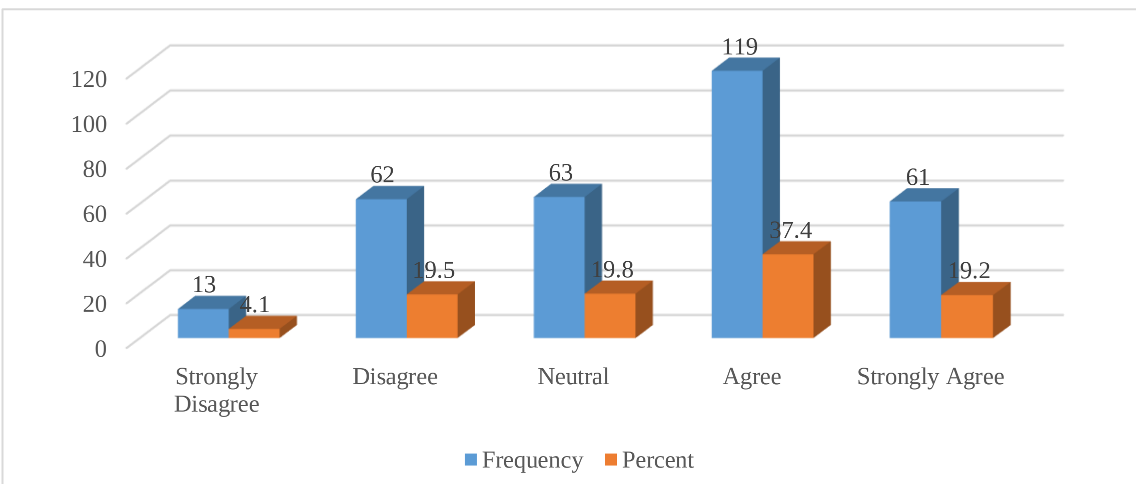

Figure 46: Digital twin implementation improves quality control.

The Confidence in the ability of digital twin implementation to enhance quality control within their organisation is shown in Figure 46 above. The idea that digital twins enhance quality control is disputed by 19.5% of participants and strongly disagreed with by 4.1%. The majority of responders (19.8%) adopt a neutral position. One encouraging finding is that respondents (37.4%) agree and 19.2% strongly agree that using digital twins improves quality control.

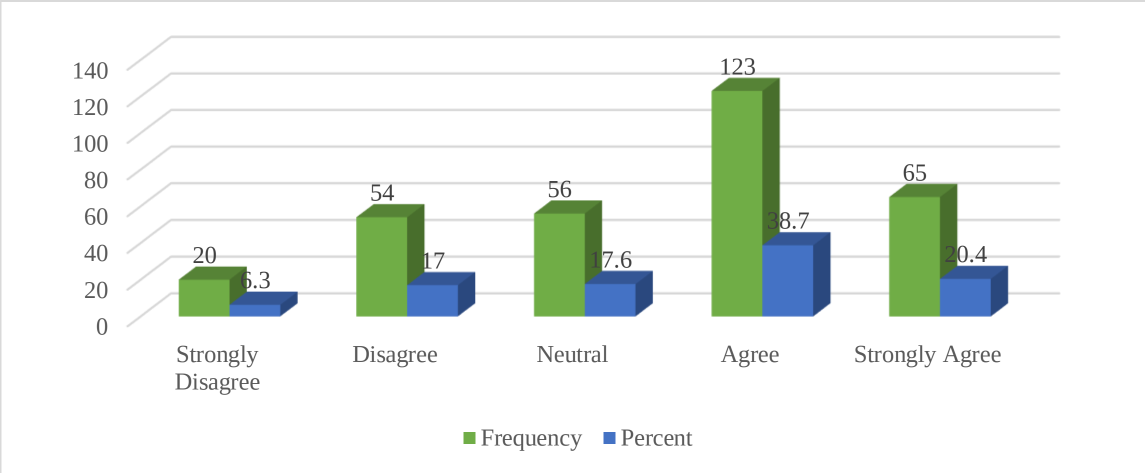

Figure 47: Digital twin adoption enhances quality standards.

The opinions on whether the use of digital twins raises overall standards for the quality of goods or services within their company are depicted in Figure 47 above. Of the participants, 17.0% disagree with this statement, and 6.3% strongly disagree. Respondents have a neutral opinion (17.6%). Positively, respondents (20.4%) strongly agree and 38.7% agree that digital twins raise the bar for quality.

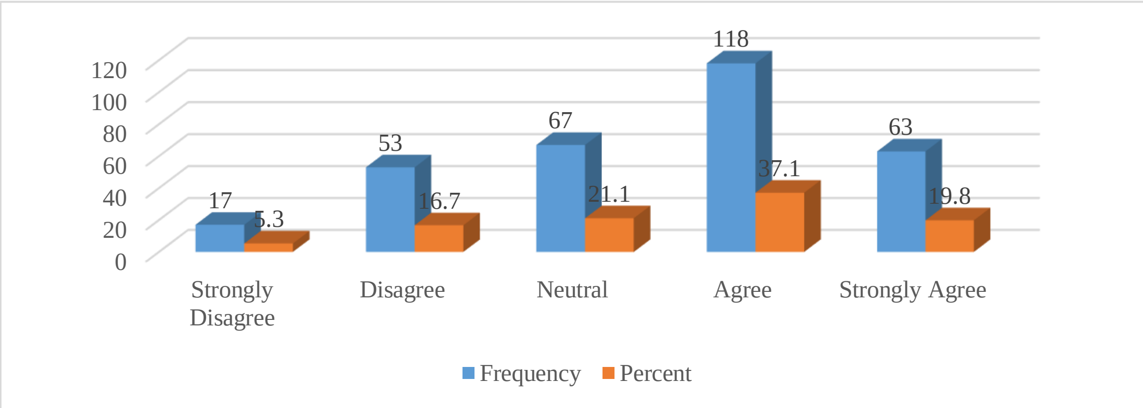

Figure 48: Digital twins optimize resources and cut costs.

The use of digital twins optimises resource utilisation and lowers operating costs, as seen in Figure 48 above. Of the participants, 16.7% disagree with this assertion, and 5.3%

strongly disagree. Respondents have a neutral position (21.1%). On the plus side, respondents strongly agree (19.8%) and agree (37.1%) believe digital twins' lower costs and improve resource efficiency.

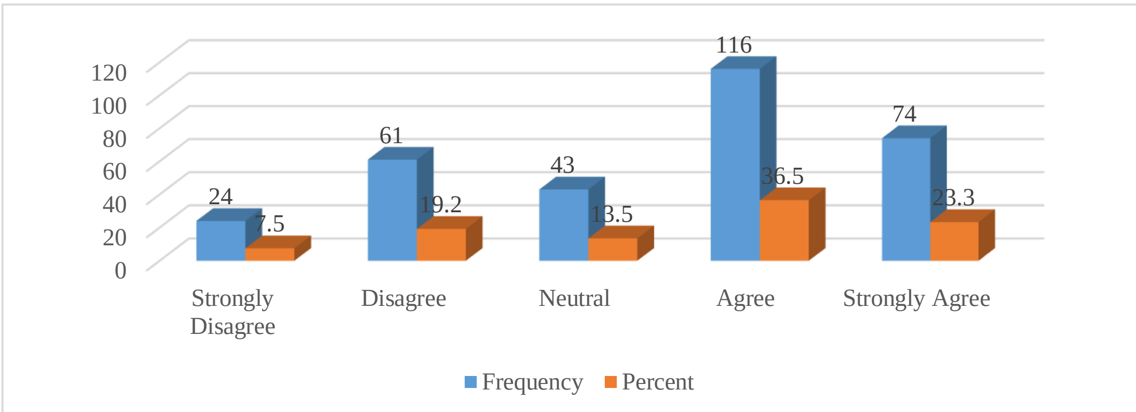

Figure 49: Digital twin adoption improves forecasting and cost efficiency.

The figure above 49 shows the respondents' belief that the use of digital twins can improve budgeting and forecasting, which will increase cost-effectiveness in their company. Participants disagree with this assertion in 19.2% of cases, and 7.5% strongly disagree. The respondent's position is neutral (13.5%). More optimistically, respondents (36.5%) agree and 23.3%) strongly think that digital twins will increase overall cost efficiency, forecasting, and budgeting.

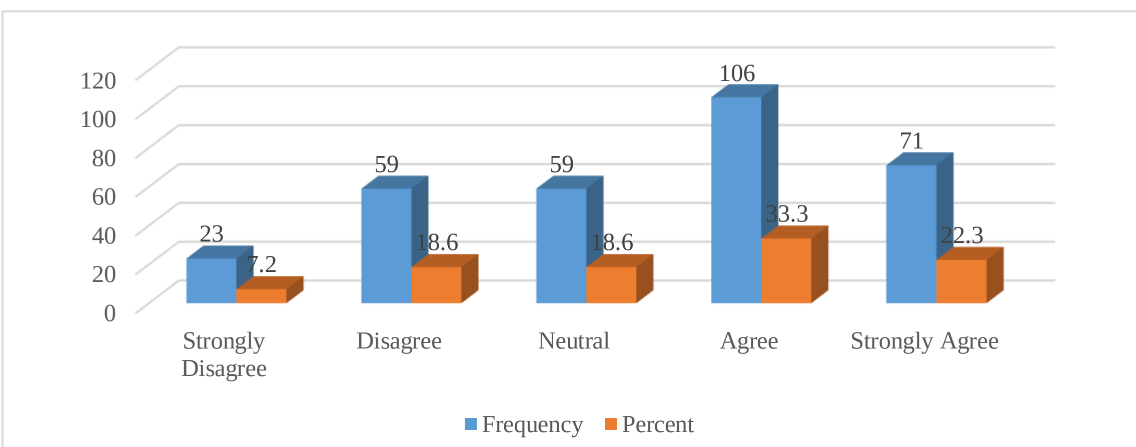

Figure 50: Digital twins enhance cost efficiency.

The effect of digital twins on cost-effectiveness in their company is shown in Figure 50 above. According to the data, 18.6% of respondents disagree with the notion that digital twins greatly increase cost efficiency, and 7.2% strongly disagree. Equally many respondents (18.6%) have a neutral viewpoint. Positively, respondents strongly agree (22.3%) and agree (33.3%) that digital twins increase cost efficiency.

Table 7 - Production Process Optimization and Cost Reduction

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Digital twin technology has helped in identifying bottlenecks and inefficiencies in our production processes.	Frequency	28	79	32	127	52
	Percent	8.8	24.8	10.1	39.9	16.4
We have been able to optimize resource utilization (e.g., manpower, machinery) through the insights provided by digital twin technology.	Frequency	10	51	37	136	84
	Percent	3.1	16	11.6	42.8	26.4
The adoption of digital twin technology has resulted in cost savings related to inventory management and stock control.	Frequency	14	49	66	130	59
	Percent	4.4	15.4	20.8	40.9	18.6
Our organization has seen a reduction in production-related costs (e.g., material wastage, rework) since implementing digital twin technology.	Frequency	8	70	49	120	71
	Percent	2.5	22	15.4	37.7	22.3
The benefits of production process optimization and cost reduction through digital twin technology have been communicated effectively within our organization.	Frequency	20	47	61	122	68
	Percent	6.3	14.8	19.2	38.4	21.4

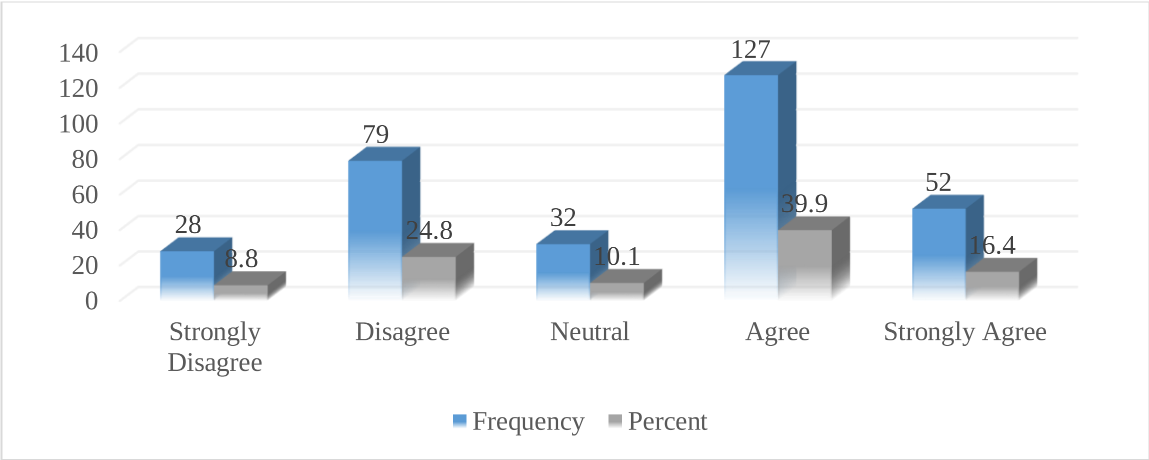

Figure 51: Digital twins identify bottlenecks and inefficiencies.

The opinions on whether digital twin technology has aided in locating manufacturing process bottlenecks and inefficiencies are depicted in Figure 51 above. Of the participants, 24.8% disagree with this assertion, and 8.8% strongly disagree. Respondents' opinions are neutral (10.1%). Positively, respondents strongly agree (16.4%) and agree (39.9%) that digital twins have helped identify industrial inefficiencies.

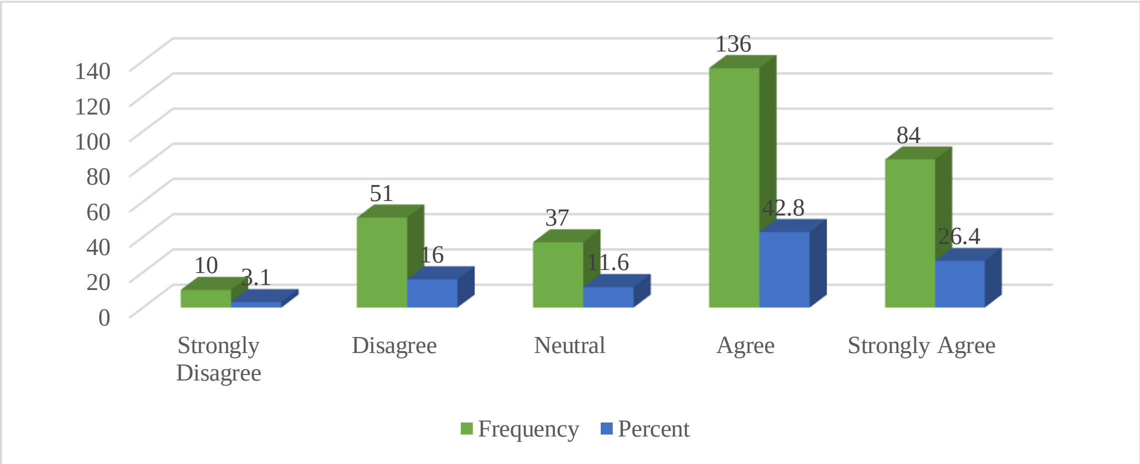

Figure 52: Digital twins optimize resource utilization.

The distribution of digital twin technology's effectiveness in maximising utilization of resources, including labour and equipment, is depicted in Figure 52 above. According to this dataset, 16.0% of respondents disagree with the statement, and 3.1% strongly disagree. 11.6% of respondents hold a neutral opinion. On the plus side, respondents (42.8%) concur and (26.4%) strongly concur that resource utilisation has been optimised thanks to digital twin insights.

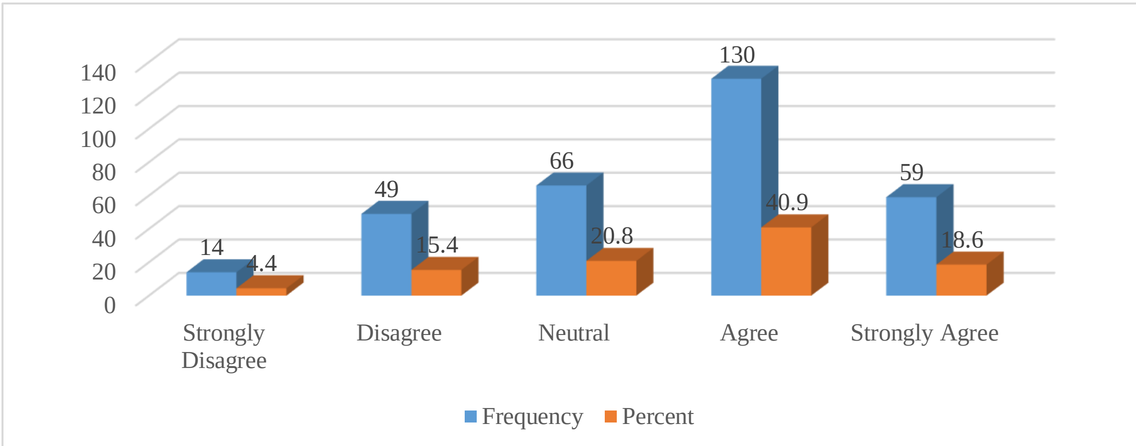

Figure 53: Digital twins reduce inventory costs.

The implementation of digital twin technology is thought to result in cost reductions in inventory management and stock control, as seen in Figure 53 above. Of those surveyed, 15.4% disagree and 4.4% strongly disagree that digital twins have resulted in significant savings. 20.8% of respondents had a neutral position. Positively, respondents agree (40.9%) and strongly agree (18.6%) that digital twins have helped reduce inventory management costs.

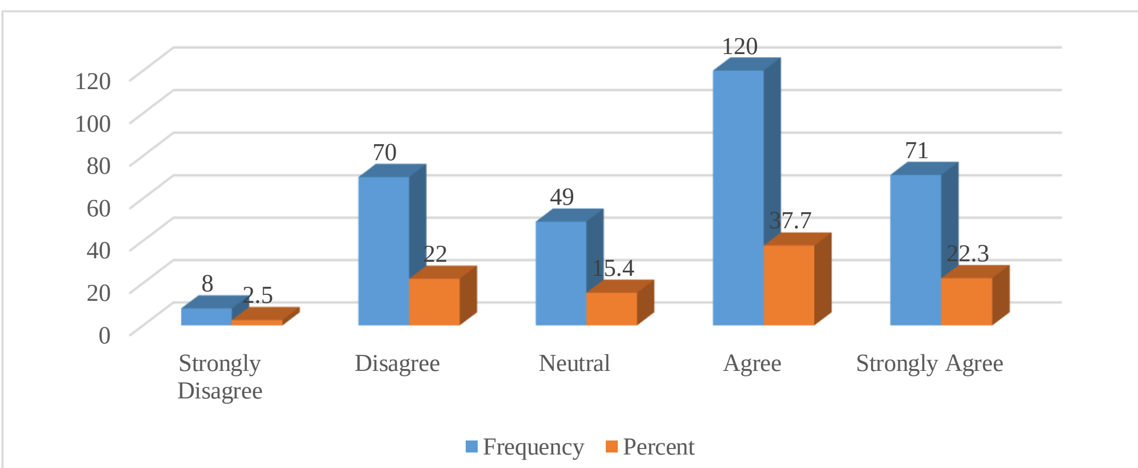

Figure 54: Digital twins cut production costs.

The data from digital twin technology has helped to lower production-related expenses including material waste and rework, as seen in Figure 54 above. 22.0% of people disagree that digital twins have contributed to a reduction in these expenses, and 2.5% strongly disagree. The respondents' stance is neutral (15.4%). On the plus side, respondents (37.7%) agree and (22.3%) strongly agree that the use of digital twins has reduced production costs.

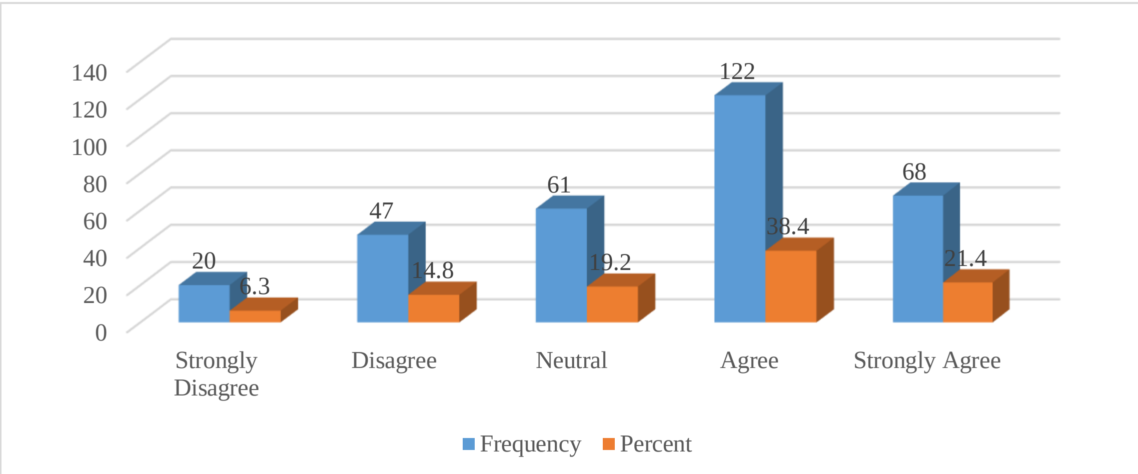

Figure 55: Digital twin benefits are effectively communicated.

The efficiency of internal communication regarding the advantages of cost reduction and production process optimisation made possible by digital twin technology is shown in Figure 55. Of those surveyed, 14.8% disagree and 6.3% strongly disagree that these advantages have been adequately conveyed. Respondents adopt a neutral position (19.2%). On the plus side, respondents agree (38.4%) and strongly agree (21.4%) that the organisation has successfully shared these benefits.

Table 8 - Integration of EPC Principles

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The integration of EPC principles with digital twin technology has improved project planning in our organization.	Frequency	24	78	42	115	59
	Percent	7.5	24.5	13.2	36.2	18.6
EPC integration with digital twin technology has increased the accuracy of project forecasting and budgeting.	Frequency	10	38	48	144	78
	Percent	3.1	11.9	15.1	45.3	24.5
The integration of EPC principles with digital twin technology has required additional training for project teams.	Frequency	4	58	66	124	66
	Percent	1.3	18.2	20.8	39	20.8
Our organization has a clear strategy for maximizing the benefits of integrating EPC principles with digital twin technology.	Frequency	15	54	53	131	65
	Percent	4.7	17	16.7	41.2	20.4
Overall, the integration of EPC principles with digital twin technology has improved project efficiency.	Frequency	15	59	40	130	74
	Percent	4.7	18.6	12.6	40.9	23.3

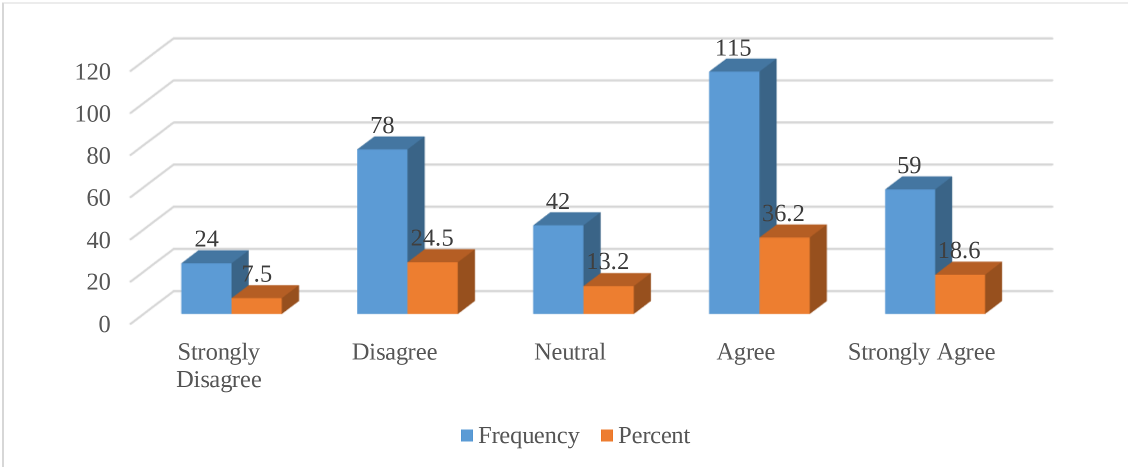

Figure 56: EPC-integrated digital twins enhance project planning.

The integration of EPC principles with digital twin technology has improved project planning in our organization, as seen in Figure 56 above. Significantly (24.5%) disagree and 7.5% strongly disagree, suggesting that they do not see an improvement. 13.2%, meanwhile, are neutral. However, the majority seem to think that this integration will have a good effect on project planning, as evidenced by the 36.2% who agree and the 18.6% who strongly agree.

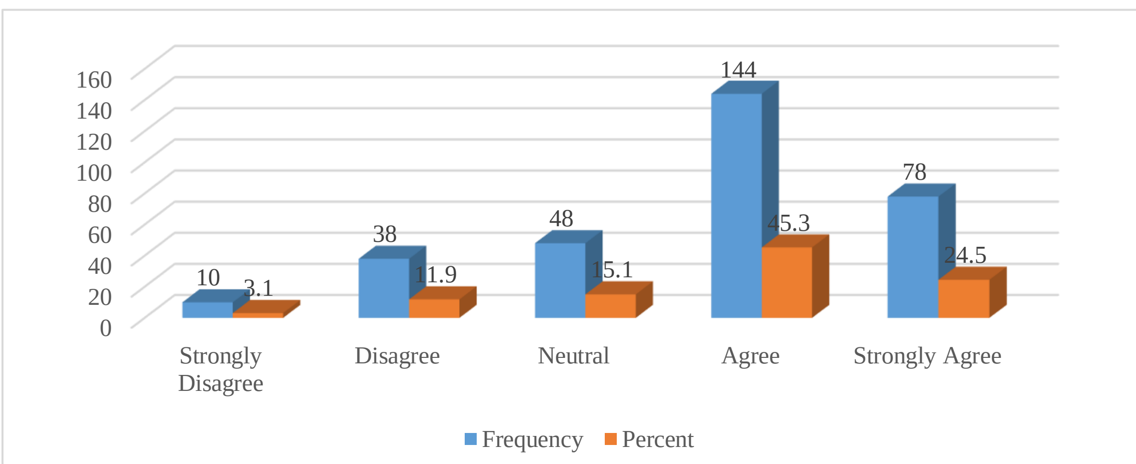

Figure 57: EPC-integrated digital twins improve forecasting and budgeting.

The above Figure 57 shows how the accuracy of project forecasting and budgeting has increased through integration of digital twin technology with Engineering, Procurement, and Construction (EPC) principles. A minority of respondents (11.9%) disagree and 3.1% strongly disagree. A neutral position is adopted by 15.1%. However, a sizable percentage of respondents (45.3%) concur that accuracy has improved as a result of the integration, with 24.5% strongly agreeing.

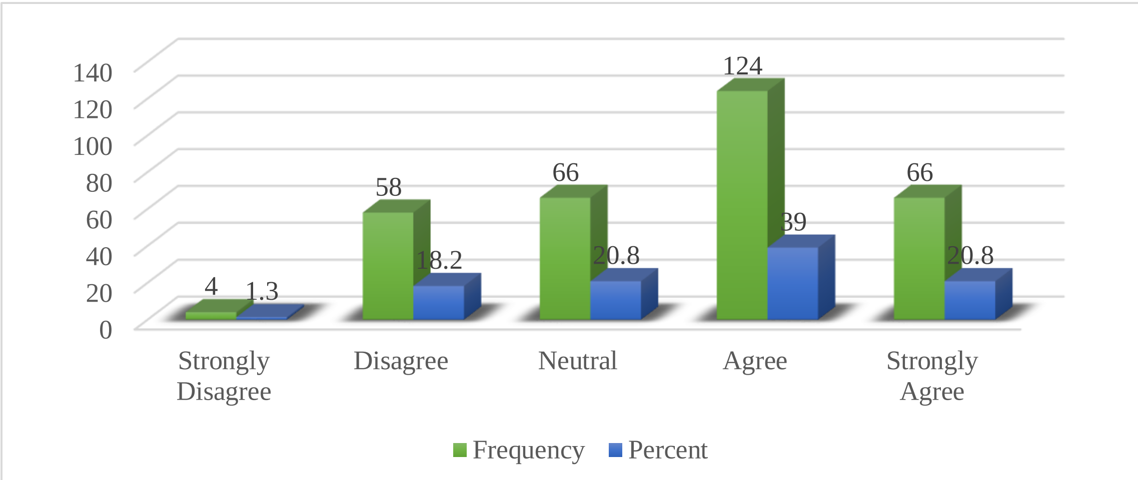

Figure 58: EPC-integrated digital twins require team training.

The integration of EPC principles with digital twin technology has required additional training for project teams is shown in Figure 58 above. Just 1.3% of respondents strongly disagree, 18.2% disagree, and 20.8% remain neutral. However, a sizable majority—39.0% agree and 20.8% strongly agree—acknowledge the need for more training.

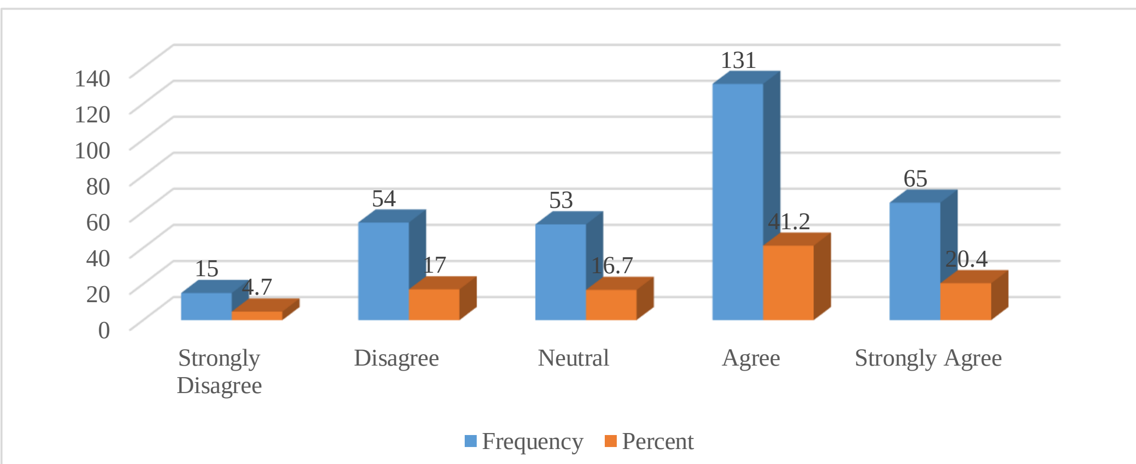

Figure 59: We have a clear strategy for EPC-digital twin integration.

The organization has a clear strategy for maximizing the benefits of integrating EPC principles with digital twin technology are displayed in Figure 59 above. Just 4.7% of respondents strongly disagree that such a method exists, compared to 17.0% who disagree and 16.7% who are neutral. On the other hand, a sizable majority (41.2%) agree that a clear strategy is in place, and another 20.4% strongly agree.

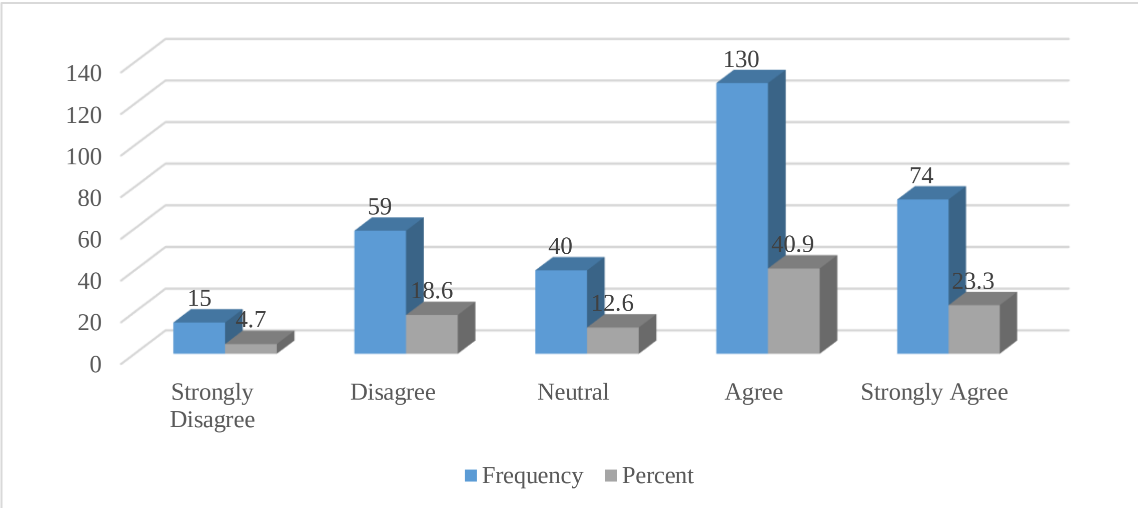

Figure 60: EPC-integrated digital twins enhance project efficiency.

The above figure 60 the respondents' views on the overall impact of integrating Engineering, Procurement, and Construction principles with digital twin technology on project efficiency. A minority of participants, specifically 4.7%, strongly disagree with the assertion that this integration has improved project efficiency, while 18.6% disagree, and 12.6% remain neutral. Meanwhile, 40.9% agree, and 23.3% strongly agree that it has indeed enhanced project efficiency.

Table 9 - Overall Operational Efficiency

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
Digital twin technology has improved the efficiency of our manufacturing processes.	Frequency	28	65	40	117	68
	Percent	8.8	20.4	12.6	36.8	21.4
We have seen a reduction in production downtime since implementing digital twin technology.	Frequency	12	33	48	138	87
	Percent	3.8	10.4	15.1	43.4	27.4
The use of digital twin technology has improved resource utilization in our organization.	Frequency	11	51	56	130	70
	Percent	3.5	16	17.6	40.9	22
We have experienced an increase in overall equipment effectiveness (OEE) since adopting digital twin technology.	Frequency	14	62	57	118	67
	Percent	4.4	19.5	17.9	37.1	21.1
Overall, digital twin technology has enhanced the performance and effectiveness of our organization's operations.	Frequency	22	48	64	132	52
	Percent	6.9	15.1	20.1	41.5	16.4

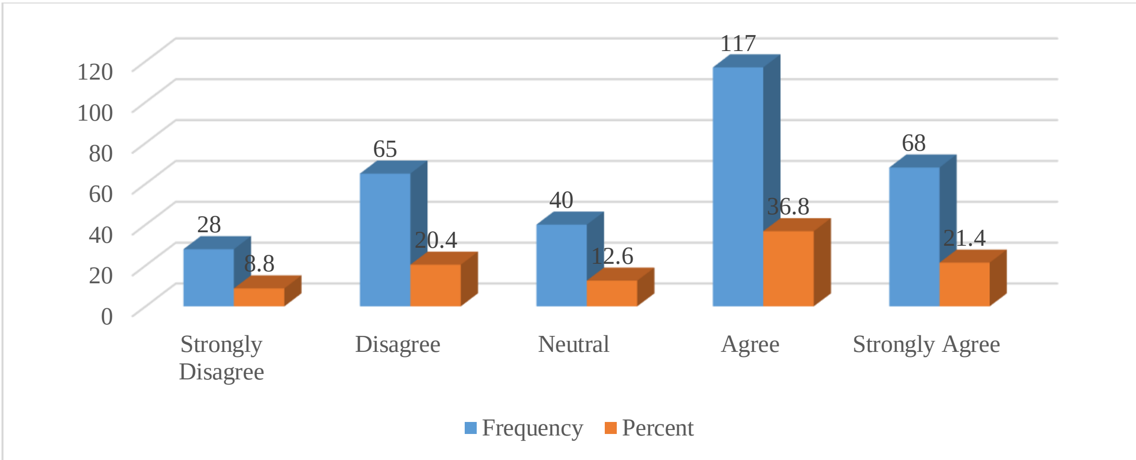

Figure 61: Digital twins enhance manufacturing efficiency.

The participants' opinions that how digital twin technology affects the effectiveness of manufacturing processes in their companies are depicted in Figure 61 above. According to the research, 20.4% of respondents disagree and 8.8% strongly disagree that digital twin technology has increased efficiency. 12.6% of participants take a neutral position. On the other hand, 58.2% of respondents agree (36.8% agree and 21.4% strongly agree) that use of digital twin technology has improved the productivity of their production operations.

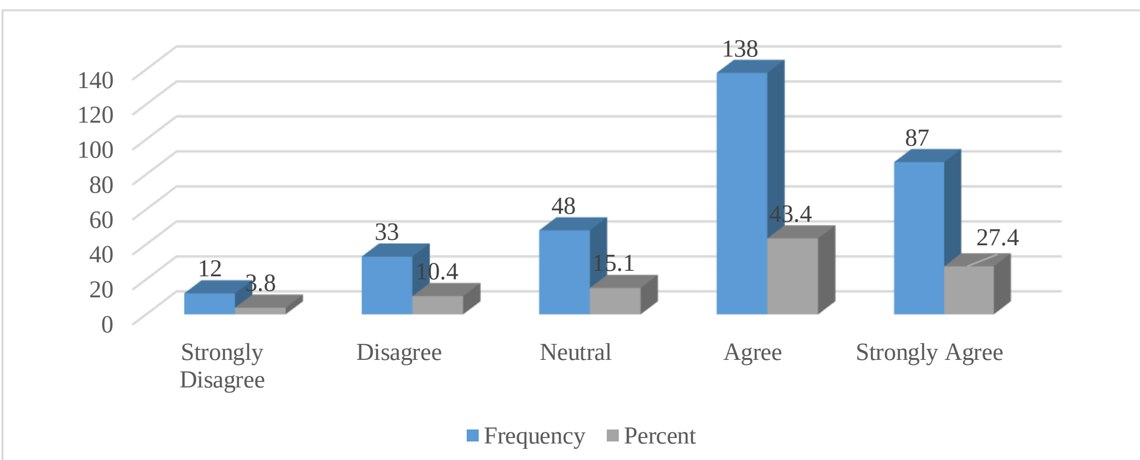

Figure 62: Digital twins reduce production downtime.

The replies about the perceived effect of digital twin technology on production downtime in organisations are shown in Figure 62 above. The findings show that 10.4% of respondents disagree and 3.8% strongly disagree with the claim that production downtime has decreased since the use of digital twin technology. 15.1% of participants had a neutral response. The majority of (43.4% agree and 27.4% strongly agree) that less production downtime has been caused by digital twin technology.

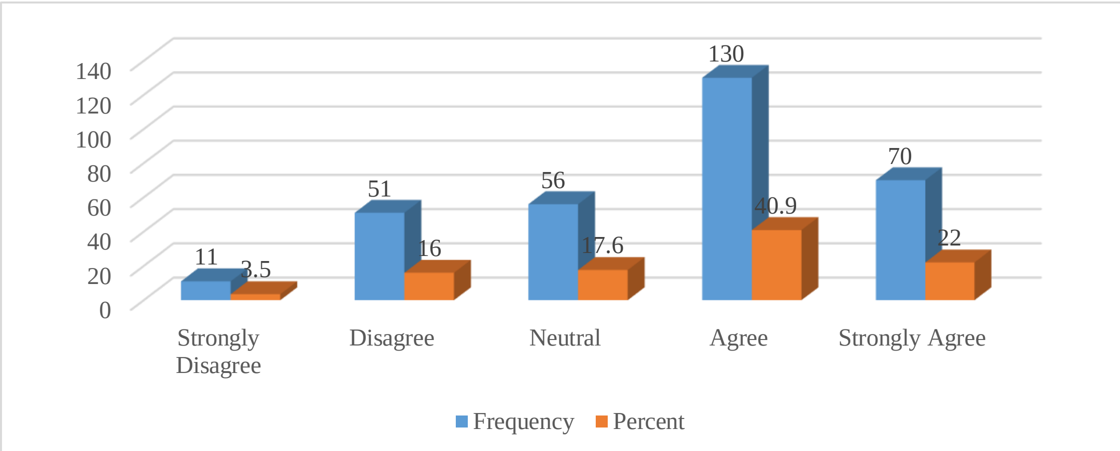

Figure 63: Digital twins improve resource utilization.

The above Figure 63 shows that 3.5% of respondents strongly disagree and 16.0% disagree that digital twin technology has improved resource utilization. Meanwhile, 62.9% agree (40.9% agree and 22.0% strongly agree), indicating a positive perception of its effectiveness in optimizing resource management within organizations.

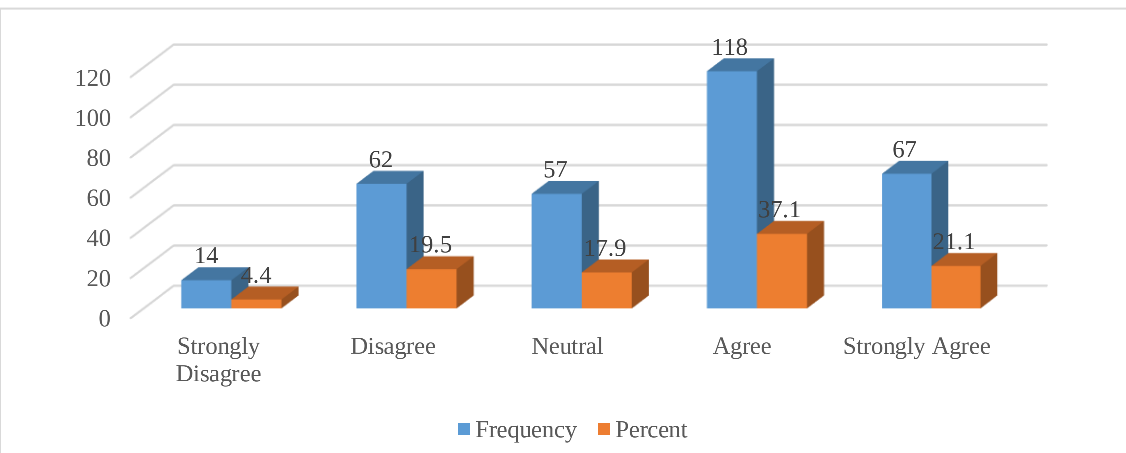

Figure 64: Digital twins boost overall equipment effectiveness (OEE).

According to Figure 64 above, 19.5% of respondents disagree and 4.4% strongly disagree that their organizations have experienced an increase in overall equipment effectiveness

(OEE) since adopting digital twin technology. On the other hand, 58.2% of respondents agree (37.1% agree and 21.1% strongly agree), indicating that most people think digital twin technology has improved their OEE.

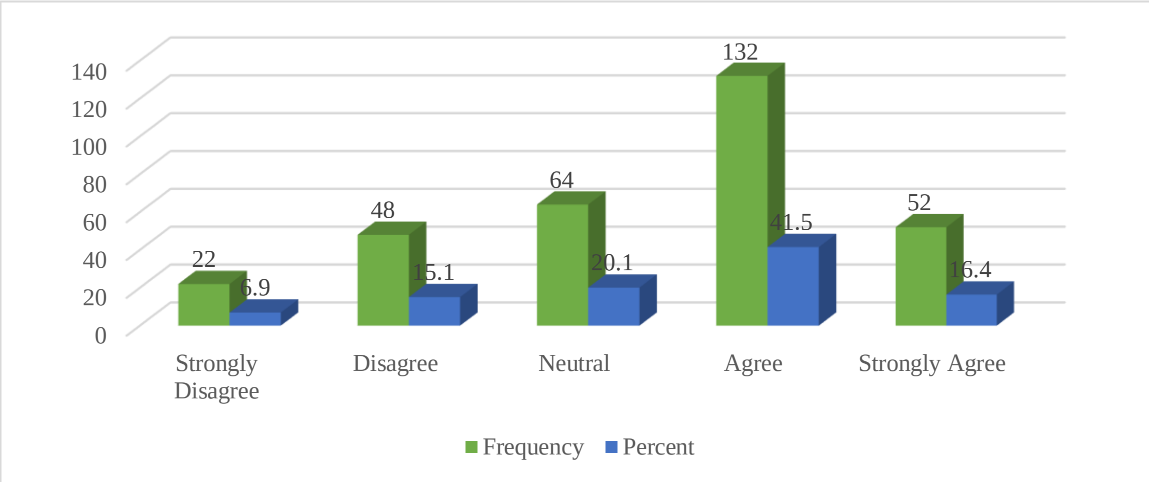

Figure 65: Digital twins enhance operational performance.

The statement that digital twin technology has enhanced the performance and effectiveness of their organization's operations is shown in the above Figure 65. whereas 6.9% of respondents strongly disagree and 15.1% disagree. Meanwhile, 41.5% agree and 16.4% strongly agree, representing that a significant portion of respondents believes in the positive impact of digital twin technology on operational performance.

Table 10 - Product Quality and Consistency

Statement	Frequency & Percent	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
The use of digital twin technology has helped in maintaining consistency in product quality.	Frequency	26	80	36	120	56
	Percent	8.2	25.2	11.3	37.7	17.6
We have seen a reduction in product defects since implementing digital twin technology.	Frequency	13	44	43	128	90
	Percent	4.1	13.8	13.5	40.3	28.3
Digital twin technology has improved our ability to meet customer specifications and requirements.	Frequency	11	59	59	133	56
	Percent	3.5	18.6	18.6	41.8	17.6
The integration of digital twin technology has improved the traceability of product components and processes.	Frequency	12	62	49	117	78
	Percent	3.8	19.5	15.4	36.8	24.5
Overall, the use of digital twin technology has enhanced the product quality and	Frequency	23	53	50	134	58
	Percent	7.2	16.7	15.7	42.1	18.2

consistency in our organization.	

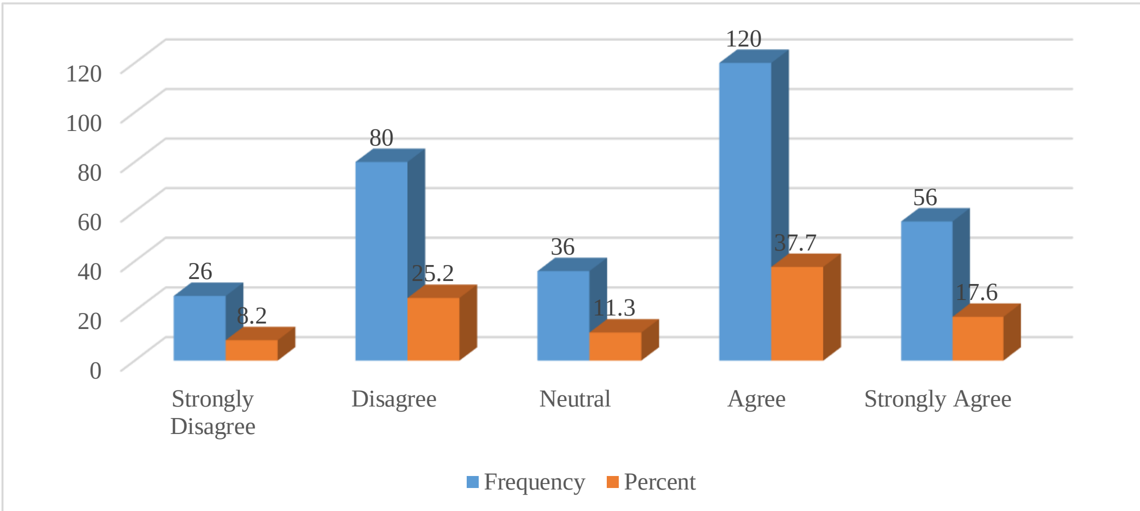

Figure 66: Digital twins ensure consistent product quality.

The implementation of digital twin technology has helped to maintain consistency in product quality, as seen in Figure 66 above. In particular, 25.2% of respondents disagree with this statement, 8.2% strongly disagree, and 11.3% are neutral. However, 17.6% strongly agree and 37.7% agree.

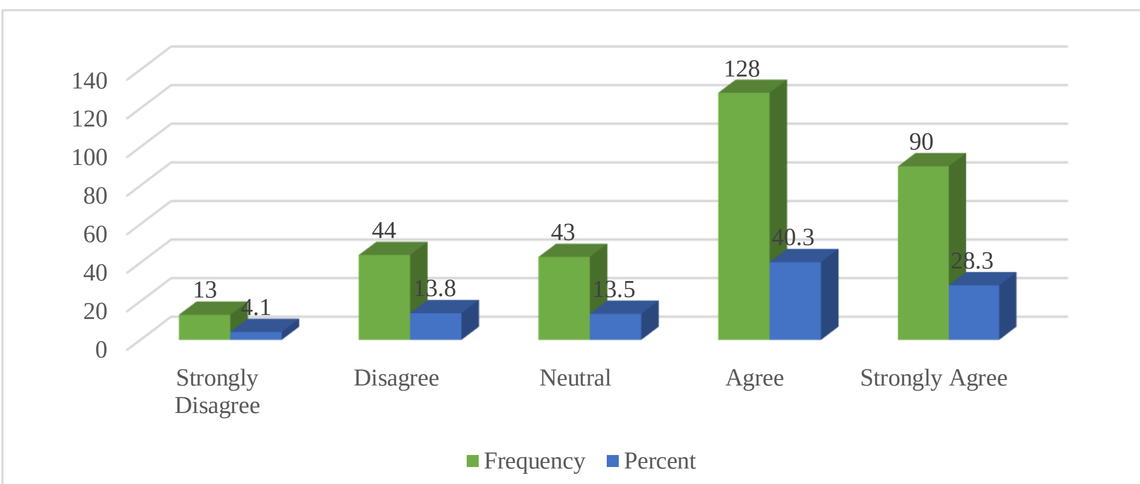

Figure 67: Digital twins reduce product defects.

The digital twin technology, respondents have reported fewer product faults, as seen in Figure 67 above. In particular, 13.8% disagree with this statement, 4.1% strongly disagree, and 13.5% are neutral. On the other hand, the majority of respondents—40.3% agree and 28.3% strongly agree—believe that digital twin technology has improved the organization's ability to reduce product faults.

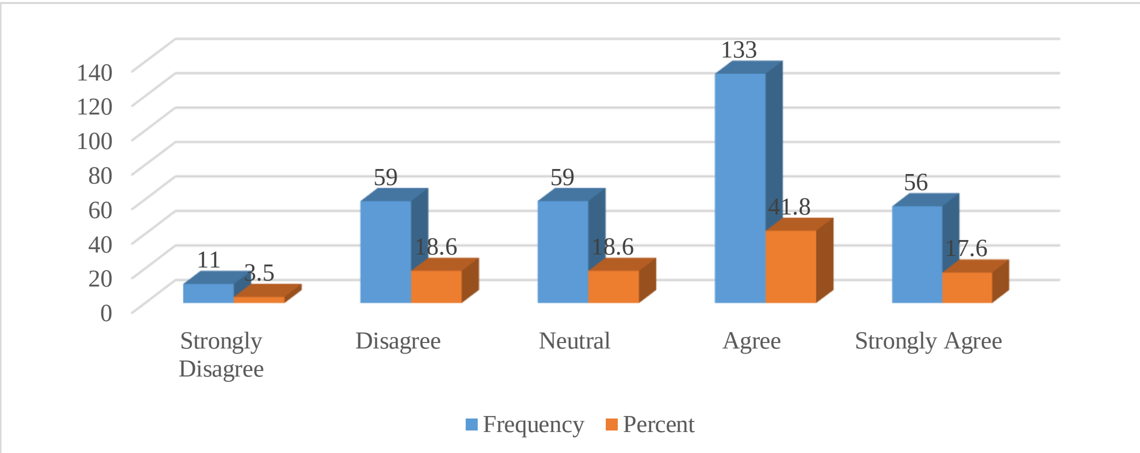

Figure 68: Digital twins enhance compliance with customer requirements.

The majority of respondents feel that digital twin technology has improved their capacity to satisfy customer demands and specifications, as seen in Figure 68 above. In particular, 18.6% of participants disagree with this statement, 3.5% strongly disagree, and another 18.6% are neutral. In contrast, 17.6% strongly agree and a sizable 41.8% agree.

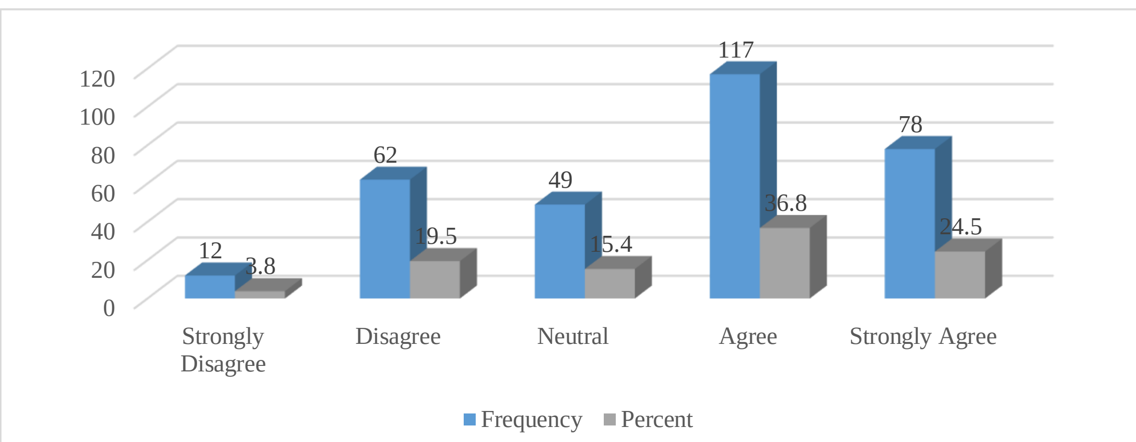

Figure 69: Digital twins enhance product traceability.

According to the above figure 69, most respondents believe that digital twin technology improves the traceability of product parts and procedures. In particular, 19.5% disagree with the statement and 3.8% strongly disagree. 15.4% of participants, meanwhile, are neutral. A significant majority of respondents (36.8% agree and 24.5% strongly agree) think that the incorporation of digital twin technology improves the traceability of products within the company.

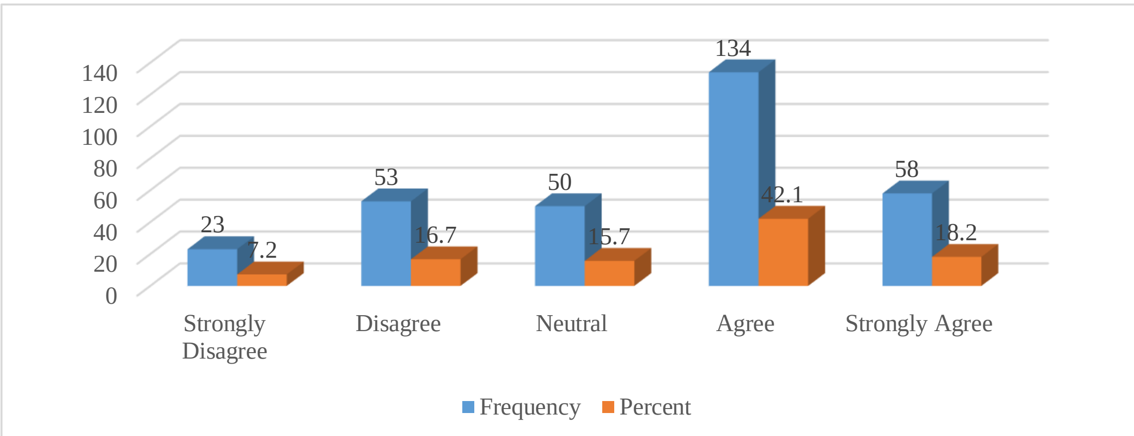

Figure 70: Digital twins improve product quality and consistency.

The above figure 70 shows that a substantial number of respondents believe that the utilization of digital twin technology has positively influenced product quality and consistency in their organization. Specifically, 7.2% strongly disagree, and 16.7% disagree with the statement. Meanwhile, 15.7% remain neutral. Conversely, 42.1% agree, and 18.2% strongly agree.

4.3 Descriptive statistics

Table 11 - Descriptive Statistics

Description	N	Mean		Std. Deviation
	Statistic	Statistic	Std. Error	Statistic
Please mention your gender	318	1.41	.028	.492
To which age group do you belong	318	2.24	.066	1.173
Please mention your Education Level	318	2.80	.048	.853
Employment Status	318	1.48	.052	.932
How many total years of work experience do you have?	318	1.98	.065	1.152
What is your annual income (in INR)	318	2.52	.083	1.485
Type of industry you are working in	318	5.86	.149	2.664
What is the size of your organisation with respect to number of employees?	318	1.79	.042	.754
Adoption of Digital Twin Technology	318	3.9088	.04502	.80290
Financial Viability	318	3.8899	.04641	.82765
Operational Excellence (Measured KPIs)	318	3.9308	.04591	.81870

Production Process Optimization and Cost Reduction	318	3.9465	.04778	.85196
Integration of EPC Principles	318	3.9623	.04667	.83221
Overall Operational Efficiency	318	3.9560	.04644	.82810
Product Quality and Consistency	318	3.9277	.04893	.87253
Valid N (listwise)	318			

The Descriptive statistics for 318 respondents about several operational and demographic characteristics are shown in Table 11 above. A wide range of ages is indicated by the gender distribution's mean of 1.41 (SD = 0.492) and the age group's mean of 2.24 (SD = 1.173). The mean for employment status is 1.48 (SD = 0.932), and mean for education levels is 2.80 (SD = 0.853). The respondents' varied financial origins are reflected in their average annual income of 2.52 (SD = 1.485) and job experience of 1.98 years (SD = 1.152). Organisation size averages 1.79 (SD = 0.754), whereas industry type has a mean score of 5.86 (SD = 2.664), indicating participation across multiple sectors. In addition to financial viability (mean = 3.89, SD = 0.828), operational excellence (mean = 3.93, SD = 0.819), and production process optimisation (mean = 3.95, SD = 0.852), adoption of digital twin technology has a noteworthy mean of 3.91 (SD = 0.802), showing good perceptions. Overall operational efficiency and product quality both average 3.96 (SD = 0.828) and 3.93 (SD = 0.873), respectively, while the integration of EPC principles scores a mean of 3.96 (SD = 0.832), indicating a generally positive opinion of digital twin technology and its advantages.

4.4 Hypotheses testing

Hypothesis 1

- **H_0:** Digital twin adoption does not positively impact financial viability and ROI.
- **H_1:** Digital twin adoption positively impacts financial viability and ROI.

Table 12 - Case Processing Summary

Indicator	Agreement Level	N	Marginal Percentage
Financial	Strongly Disagree	1	0.3%
Viability	Disagree	5	1.6%
	Neutral	107	33.6%
	Agree	120	37.7%
	Strongly Agree	85	26.7%
Valid		318	100.0%
Missing		0	
Total		318	

According to Table 12 above, respondents' perceptions of financial viability are largely positive. Just 1.9% of the 318 valid replies disagreed, and 33.6% were neutral, which may indicate ambivalence. 64.4% of respondents agreed or strongly agreed, indicating a generally optimistic view of financial feasibility with little resistance.

Table 13 - Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	299.770			
Final	96.347	203.422	1	.000
Link function: Logit.				

The above Table 13 The model summary shows a significant improvement with predictors added. The **-2 Log Likelihood** decreases from 299.770 to 96.347, and the **Chi-Square** value of 203.422 (df = 1, **p = .000**) confirms that the predictors greatly enhance the model fit using the logit link function.

Table 14 - Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	685.734	11	.000
Deviance	62.682	11	.000
Link function: Logit.			

The above Table 14 presents goodness-of-fit results. Both the **Pearson Chi-Square** (685.734, **p = .000**) and **Deviance** (62.682, **p = .000**) indicate significant fit using the logit link function, though the high Pearson Chi-Square suggests possible overdispersion.

Table 15 - Pseudo R-Square

Cox and Snell	.473
Nagelkerke	.523
McFadden	.273
Link function: Logit.	

The model's pseudo-R-squared values are shown in Table 15 above. The values for Cox and Snell, Nagelkerke, and McFadden are.473,.523, and.273, respectively. With the Nagelkerke R-squared showing the best fit among the three, these figures imply that model explains a moderate amount of the variance in the result.

Table 16 - Parameter Estimates

		Estimate	Std. Error	Wald	df	Sig.	95% Confidence Interval	
							Lower Bound	Upper Bound
Threshold	[FV = 1.00]	2.377	1.011	5.527	1	.019	.395	4.359
	[FV = 2.00]	4.195	.688	37.207	1	.000	2.847	5.543
	[FV = 3.00]	8.429	.729	133.626	1	.000	6.999	9.858
	[FV = 4.00]	11.153	.848	172.816	1	.000	9.490	12.815
Location	ADTT	2.423	.194	156.353	1	.000	2.043	2.803

Link function: Logit.

The results in Table 16 provide evidence for Hypothesis 1, which proposes that digital twin adoption (ADTT) positively impacts financial viability (FV) and ROI. The **parameter estimate for ADTT** is **2.423** with a **Std error of .194** and a significant **Wald value of 156.353 (p = .000)**, suggesting a positive relationship between digital twin adoption and financial viability.

The hypothesis is further supported by the statistically significant results of the threshold estimates for the FV categories, each of which had p-values smaller than 0.05. Adoption of digital twins consistently improves financial viability and return on investment (ROI), as seen by the progressively substantial thresholds shown by higher financial viability levels (FV = 2.00, FV = 3.00, and FV = 4.00). The adoption of digital twins has a strong positive impact, as evidenced by the rejection of the null hypothesis (H_0) in favour of the alternative (H_1).

Hypothesis 2

- **H_0:** Digital twins do not have a significant relationship with improved operational excellence (via KPIs).
- **H_1:** Digital twins have a significant relationship with improved operational excellence (via KPIs).

Nonparametric Correlations

Table 17 - Correlations

Correlation Variables			Adoption of Digital Twin Technology	Operational Excellence (Measured KPIs)
Spearman's rho	Adoption of Digital Twin Technology	Correlation Coefficient	1.000	.726**
		Sig. (2-tailed)	.	.000
		N	318	318
	Operational Excellence (Measured KPIs)	Correlation Coefficient	.726**	1.000
		Sig. (2-tailed)	.000	.
		N	318	318

**. Correlation is significant at the 0.01 level (2-tailed).

Table 17 presents the correlation analysis related to Hypothesis 2, which posits a significant relationship between digital twins and improved operational excellence via key performance indicators (KPIs). The Spearman's rho correlation coefficient between the **adoption of digital twin technology** and **operational excellence (measured KPIs)** is **0.726**, with a significance level of **.000**. This strong positive correlation shows that as adoption of digital twin technology increases, so does operational excellence.

The results indicate a significant connection at the 0.01 level (2-tailed) with both variables having N = 318. This enables the alternative hypothesis (H_1) to be accepted in favour of the null hypothesis (H_0). As a result, the data backs up the claim that better operational excellence through KPI assessment is significantly correlated with digital twins.

Hypothesis 3

- **H_0:** Digital twins do not significantly impact cost reduction in production processes.
- **H_1:** Digital twins significantly impact cost reduction in production processes.

PLUM - Ordinal Regression

Table 18 - Case Processing Summary

Indicator	Agreement Level	N	Marginal Percentage
Production Process Optimization and Cost Reduction	Disagree	11	3.5%
	Neutral	91	28.6%
	Agree	120	37.7%
	Strongly Agree	96	30.2%
Valid		318	100.0%
Missing		0	
Total		318	

The above Table 18 presents the case processing summary for Hypothesis 3, which examines the impact of digital twins on cost reduction in production processes. Among the 318 valid responses, only **3.5% (11 respondents)** disagreed with the statement regarding cost reduction, while **28.6% (91 respondents)** remained neutral, indicating uncertainty or ambivalence about the impact.

A significant majority, 37.7% (120 respondents) agreed, and 30.2% (96 respondents) strongly agreed, suggesting that the use of digital twins to lower production costs is generally seen favourably. With no missing data, the general sentiment points to a positive perception of digital twins' ability to reduce costs and optimise manufacturing processes. This distribution shows that digital twins have a major impact on lowering production process costs, supporting the alternative hypothesis (H_1) and rejecting the null hypothesis (H_0).

Table 19 - Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	255.213			
Final	71.148	184.065	1	.000
Link function: Logit.				

Table 19 displays the facts on model fitting. The resulting model's 71.148 value is significantly less than the -2 Log Likelihood of 255.213 for the intercept-only model. The Chi-Square score is 184.065 with one df and a significance level of.000, indicating that the addition of predictors greatly enhances model fit. The final model's improved explanatory power utilising the logit link function is demonstrated by this decrease in log-likelihood and the substantial Chi-Square.

Table 20 - Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	149.851	8	.000
Deviance	33.202	8	.000
Link function: Logit.			

Table 20 above shows the goodness-of-fit statistics for the model. With eight degrees of freedom (df), the deviation is 33.202 and the Pearson Chi-Square score is 149.851. Both tests have a significance level of.000, indicating that the model and the data fit well. The results suggest that the model effectively captures the underlying relationships in the data using the **logit link function**.

Table 21 - Pseudo R-Square

Cox and Snell	**.439**
Nagelkerke	.483
McFadden	.240
Link function: Logit.	

The model's pseudo-R-squared values are shown in Table 21. The values for Cox and Snell, Nagelkerke, and McFadden are .439,.483, and.240, respectively. With the highest Nagelkerke R-squared, indicating the best fit among the three, these data show a moderate explanation of the variance in the outcome variable.

Table 22 - Parameter Estimates

		Estimate	**Std. Error**	**Wald**	**df**	**Sig.**	**95% Confidence Interval**	
							Lower Bound	**Upper Bound**
Threshold	[PPO_CR = 2.00]	4.091	.644	40.361	1	.000	2.829	5.353
	[PPO_CR = 3.00]	7.356	.678	117.761	1	.000	6.027	8.684
	[PPO_CR = 4.00]	9.912	.785	159.576	1	.000	8.374	11.450
Location	ADTT	2.197	.183	143.839	1	.000	1.838	2.557
Link function: Logit.								

The above Table 22 presents the parameter estimates for the model assessing the influence of digital twin adoption (ADTT) on production process optimization and cost reduction (PPO_CR). The threshold estimates reveal significant values for each level of PPO_CR: **4.091** for PPO_CR = 2.00 (Std. Error = **.644**, Wald statistic = **40.361**, p = **.000**); **7.356** for PPO_CR = 3.00 (Std. Error = **.678**, Wald statistic = **117.761**, p = **.000**); and **9.912** for PPO_CR = 4.00 (Std. Error = **.785**, Wald statistic = **159.576**, p = **.000**). The ADTT parameter estimate is 2.197 (Std. Error =.183, Wald statistic = 143.839, p =.000), suggesting a strong positive correlation between the deployment of digital twins and improved cost reduction and manufacturing process optimisation. The conclusion that the adoption of digital twins has a considerable impact on production results is further supported by the fact that the confidence intervals for all estimates are above zero.

Hypothesis 4

- **H_0:** There is no positive relationship between digital twin usage and increased operational efficiency.
- **H_1:** There is a positive relationship between digital twin usage and increased operational efficiency.

Nonparametric Correlations

Table 23 - Correlations

Correlation Variables			Adoption of Digital Twin Technology	Overall Operational Efficiency
Spearman's rho	Adoption of Digital Twin Technology	Correlation Coefficient	1.000	.675**
		Sig. (2-tailed)	.	.000
		N	318	318
	Overall Operational Efficiency	Correlation Coefficient	.675**	1.000
		Sig. (2-tailed)	.000	.
		N	318	318

**. Correlation is significant at the 0.01 level (2-tailed).

The above Table 23 presents the correlation analysis for Hypothesis 4, which examines the relationship between digital twin usage and increased operational efficiency. The Spearman's rho correlation coefficient between the **adoption of digital twin technology** and **overall operational efficiency** is **0.675**, with a significance level of **.000**. This strong positive correlation indicates that higher implementation of digital twin technology is associated with increased operational efficiency.

The results show a significant connection at the 0.01 level (2-tailed) with both variables having N = 318, enabling the alternative hypothesis (H_1) to be accepted in favour of the null hypothesis (H_0). The use of digital twins and improved operational efficiency are therefore positively correlated, according to the findings.

Hypothesis 5

- **H_0:** Digital twins do not positively impact product quality and consistency.
- **H_1:** Digital twins positively impact product quality and consistency.

PLUM - Ordinal Regression

Table 24 - Case Processing Summary

Indicator	Agreement Level	N	Marginal Percentage
Overall Operational Efficiency	Disagree	9	2.8%
	Neutral	89	28.0%
	Agree	127	39.9%
	Strongly Agree	93	29.2%
Valid		318	100.0%
Missing		0	
Total		318	

The above Table 24 provides the case processing summary for Hypothesis 5, which investigates the impact of digital twins on product quality and consistency. Out of 318 valid responses, only **2.8% (9 respondents)** disagreed with the statement regarding product quality and consistency, while **28.0% (89 respondents)** remained neutral, reflecting some uncertainty or ambivalence.

A significant majority, 39.9% (127 respondents) agreed, and 29.2% (93 respondents) strongly agreed, suggesting that the utilisation of digital twins to improve product quality and consistency is generally seen as favourable. Overall attitude points to a positive assessment of digital twins' ability to enhance product results, with no missing data. This distribution supports the claim that digital twins have a favourable impact on product quality and consistency by offering evidence to reject the null hypothesis (H_0) in favour of the alternative hypothesis (H_1).

Table 25 - Model Fitting Information

Model	-2 Log Likelihood	Chi-Square	df	Sig.
Intercept Only	237.755			
Final	55.332	182.423	1	.000
Link function: Logit.				

Table 25 above displays the model fitting data. The final model's -2 Log Likelihood is 55.332, significantly less than the intercept-only model's 237.755. At a significance level of.000 and with 1 degree of freedom (df), the Chi-Square statistic is 182.423, which shows that adding predictors significantly improves model fit.

Table 26 - Goodness-of-Fit

	Chi-Square	df	Sig.
Pearson	37.201	8	.000
Deviance	19.133	8	.014
Link function: Logit.			

The model's goodness-of-fit statistics are shown in Table 26 above. With eight degrees of freedom (df), the Pearson Chi-Square value is 37.201, and the Deviance is 19.133. The Deviance is significant at.014, and the Pearson Chi-Square is significant at.000. These results show that the model successfully captures the underlying relationships and fits the data.

Table 27 - Pseudo R-Square

Cox and Snell	**.437**
Nagelkerke	.482
McFadden	.242
Link function: Logit.	

The model's pseudo-R-squared values are shown in Table 27 above. The values for Cox and Snell, Nagelkerke, and McFadden are .437,.482, and.242, respectively. With the greatest Nagelkerke R-squared, which indicates the best fit among the three, these data point to a moderate amount of variance explained by the model.

Table 28 - Parameter Estimates

		Estimate	**Std. Error**	**Wald**	**df**	**Sig.**	**95% Confidence Interval**	
							Lower Bound	**Upper Bound**
Threshold	[OOE = 2.00]	3.782	.653	33.540	1	.000	2.502	5.062
	[OOE = 3.00]	7.180	.673	113.853	1	.000	5.861	8.499
	[OOE = 4.00]	9.874	.787	157.306	1	.000	8.331	11.417
Location	ADTT	2.172	.183	141.038	1	.000	1.813	2.530
Link function: Logit.								

The above Table 28 presents the parameter estimates for the model evaluating the impact of digital twin adoption (ADTT) on overall operational efficiency (OOE). The threshold estimates for each level of OOE are as follows: 3.782 for OOE = 2.00 (Std. Error = .653, Wald statistic = 33.540, p = .000); 7.180 for OOE = 3.00 (Std. Error = .673, Wald statistic = 113.853, p = .000); and 9.874 for OOE = 4.00 (Std. Error = .787, Wald statistic = 157.306, p = .000).

According to the ADTT parameter estimate of 2.172 (Std. Error =.183, Wald statistic = 141.038, p =.000), there is a noteworthy positive correlation between the adoption of digital twins and increases in overall operational efficiency. The conclusion that the deployment of digital twins improves operational efficiency is further supported by the fact that the confidence intervals for all estimates are above zero.

Hypothesis 6

- **H_0:** The integration of EPC principles does not significantly correlate with the increased operational efficiency.
- **H_1:** The integration of EPC principles significantly correlates with the increased operational efficiency

Nonparametric Correlations

Table 29 - Correlations

Correlation Variables			Integration of EPC Principles	Overall Operational Efficiency
Spearman's rho	Integration of EPC Principles	Correlation Coefficient	1.000	.704**
		Sig. (2-tailed)	.	.000
		N	318	318
	Overall Operational Efficiency	Correlation Coefficient	.704**	1.000
		Sig. (2-tailed)	.000	.
		N	318	318

**. Correlation is significant at the 0.01 level (2-tailed).

The above Table 29 presents the correlation analysis for Hypothesis 6, which examines the relationship between the integration of EPC (Engineering, Procurement, and Construction) principles and increased operational efficiency. The Spearman's rho correlation coefficient between the integration of EPC principles and overall operational efficiency is 0.704, with a significance level of .000. This strong positive correlation indicates that greater integration of EPC principles is associated with enhanced operational efficiency.

Considering N = 318 for both variables, the results show a significant connection at the 0.01 level (2-tailed), which permits the alternative hypothesis (H_1) to be accepted in favour of the null hypothesis (H_0). Therefore, there is evidence to support the claim that there is a considerable correlation between greater operational efficiency and the incorporation of EPC concepts.

CHAPTER V:

DISCUSSION

5.1 Discussion of Results

The advent of Industry 4.0 has the ability to boost efficiency and adaptability, lower costs, and provide businesses a competitive edge. The current tendencies towards Industry 5.0 present an alternative perspective that aims to create a resilient, sustainable, and people-centered industry. An even more comprehensive strategy for research, technology, and innovation, Industry 5.0 aims to increase the sustainability of all sectors of the economy and offer practical solutions to the escalating technical, social, and economic issues.

A “digital twin” (DT) is a two-way data integration between a real-world and digital asset (Grieves & Vickers, 2016). Digital Twin is at the front of the transformation being ushered in by Industry 4.0/5.0 due to its improved data analytics and IoT connectivity. For various issues relating to the digital-physical interface, such defect identification and predictive maintenance, the data-rich environment enabled by the "Internet of Things" (IoT) in conjunction with data analytics is an essential resource. Before examining a possible Industry 4.0 architecture that can make use of DT technologies to support sustainable industry, this article first addresses sustainable manufacturing and anomaly detection in patient care. First, the study focusses on manufacturing, healthcare, and building.

With the use of tracking, monitoring, and simulation, manufacturers may save time, cut costs, become more robust to disruptions, and be more environmentally friendly (Fuller et al., 2020). Therefore, digital twins with these features could greatly influence this industry (He & Bai, 2021).

Manufacturing has been one of the most promising application domains for DT since its proposal, drawing significant attention from both academics and industry.

Although DT has not been definitively defined, it is widely acknowledged that DT must comprise a physical entity, a virtual entity, and the connections between them (Cimino et al., 2019; Tao, Zhang, Liu, et al., 2019). A virtual entity, acting as a stand-in for a physical one, might take in the operating data of the physical one in real time, process it, and then utilise simulation to produce decision-supporting prediction findings. In this way, the physical entity's performance could be enhanced or idealized. The essentiality of two-way communication between physical and virtual entities in establishing a true DT is evident (Cimino et al., 2019). So, according to (Tao, Zhang, & Nee, 2019). a whole DT should be described along five dimensions: physical component, virtual part, connection, data, and service. However, in a separate publication, they detailed nine distinct service offerings from DT (Tao et al., 2018). Equipment C. Liu et al. (2019); Luo et al. (2019), workstation C. Liu et al. (2019); Söderberg et al. (2017), production line H. Zhang et al. (2017) and production system Fan et al. (2021), are some of the scales at which studies on DT in manufacturing have been demonstrated.

In their study, Luo et al. (2019) utilized DT on CNC machine tools to enhance their intelligence, optimize their running modes, decrease the likelihood of unexpected failure, and improve stability. In their 2019 study, Liu et al. (2019) looked at the cyber-physical production system's link modelling and data modelling of CNC machine tools. Digital twins of CNC machine tools have been effectively implemented using two widely used standards for industrial equipment data exchange and information modelling, MT Connect and OPC UA. In their study, Havard et al. (2019) utilized DT to create a collaborative assembly workstation for humans and robots.

With DT’s ergonomic assessment and safety issue simulation, workplace arrangement and human worker’s behaviors, which can potentially disrupt the flow of robotic production lines, are smoothed out. An attempt toward developing the DT of a sheet metal part assembly line was undertaken by Söderberg et al. (2017) have DT that can take data from both individuals and batches of components and utilize it to make modifications batch-wise or in real-time in line with each part.

Zhang et al. (2017) used DT to improve the hollow glass production line's design. We may ascertain the production line's operating parameters, such as order delivery time, production takt time, and production load, with the use of DT's powerful simulation capabilities in order to optimise iteratively. In their study, Fan et al. (2021), highlighted the importance of digital twin visualization in flexible production systems. They looked at the visualization approach of high-value information to build a lightweight architecture without compromising its functionalities. This includes stages such as life cycle planning, design, debugging, and service. Due to space constraints, this review only offered a systematic overview of the selected literature on DT applications in manufacturing; there is a great deal of work in this area. (Lu et al., 2020).

5.2 Discussion of Research Question One

It is crucial to understand how "digital twin" technology (DT) brings such differentiating value for economy across industries through cost reduction, improved productivity, and positive "return on investment" (ROI). The study results show that DT adoption yields significant economic benefits to organizations that are mainly through resource optimization, productivity increases, and process efficiency improvements which are consistent with other studies (Jones et al., 2020; Negri et al., 2017). To this end, the findings underscore the importance of DT in raising awareness of its importance in lowering operational costs, resource consumption, and consequently, ROI. Most of the respondents (62.9%) either partly or fully agree with the statement that use of DT technology has assisted their organization to better employ its resources and practice more efficient operations at lower costs. This is consistent with the work of Tao, Zhang, Liu, et al. (2019) who found DT to be used by organizations for simulating real-time scenarios to reduce waste and optimize asset management. In terms of positive feedback on productivity gains (37.7% agree, 19.8% strongly agree), this supports idea that DT has the potential to generate substantial operational improvements, as argued also by Kritzinger et al. (2018), in their research on the use of DT.

The enhancement of decision-making process is a critical part of the economic benefits of DT, which leads to short-term and long-term cost savings. The respondents claimed that digital twin technology has considerably helped in making decisions and strategic planning; 34.9 % agreed and 23.9 % strongly agreed. This is in line with findings by Grieves & Vickers (2016) that digital twins that allow for real time data insight to support better-informed decisions can shorten the time and cost involved in decision-making. In addition, the responses show how digital twin integration leads to more accurate budgeting and forecasting (45.3% agree, 24.5% strongly agree). By integrating these applications, companies can anticipate and mitigate potential issues, particularly in manufacturing and engineering, industries with high operational costs, which could be reduced by accurate forecasting to mitigate financial risks of delays and resource shortages (Fuller et al., 2020).

Responses confirm that economic impact of digital twins on cost efficiency is validated further in that DT lead to lower downtime and production-related costs, two drivers of ROI. Specifically, respondents agreed or strongly agreed they saw reduced production downtime (43.4%) or reduced production costs (similar to material wastage and rework) (37.7%), due to the adoption of DT. This finding is consistent with other literature, which holds that digital twins help improve operational reliability by predicting and preventing bottlenecks and inefficiencies (Boschert & Rosen, 2016; Tao, Zhang, Liu, et al., 2019) which in turn reduces downtime and related costs. Compared to conventional methods, being proactive makes the digital twin more of an approach to maintenance and optimization, with less dependency on reactive measures that are more costly and disruptive. The reduction in inventory and stock management costs (40.9% agree, 18.6% strongly agree) further reinforces the economic value of digital twins, a benefit highlighted in the work of Uhlemann et al. (2017), who describe digital twins as an effective tool for optimizing supply chains and reducing inventory holding costs.

In addition, DT helps increase revenue generation by enhancing product quality and customer satisfaction. According to the respondents, they agree (39.4%) or strongly agree (22.3%) that digital twin technology is positively correlated with customer satisfaction which indicates that digital twin technology helps organizations to achieve customers' expectations. This echoes finding of Lee et al. (2018), who found that companies using DT can simulate customer requirements, and adjust production processes accordingly with higher customer loyalty or more revenue. The ROI comes from improved product quality, which is supported by responses that indicate that digital twins improve quality control efforts (37.4% agree; 19.2% strongly agree), reducing defect-related costs and building brand reputation. According to Stark et al. (2019), the ability to be sure that products are consistently quality is a great capability in highly competitive industries, where product recalls and rework can have a massive effect on profitability. Expenses to be saved come from quality improvements, which also give you a competitive edge, which may help boost income.

Direct financial ROI such as cost savings and revenue growth, as well as direct efficiency and risk avoidance, are all assessed in terms of ROI for investments in digital twin. Respondents were also asked to rate their approval of some metrics for an effective ROI assessment of DT Fuller et al. (2020), including reduction in downtime, improvement in equipment effectiveness and cost benefits from inventory management. The data on respondents' perception of a favourable ROI (41.2% agree, 23.3% strongly agree) echoes the literature which stresses the importance of these metrics in determining whether digital twins are economically viable. In addition, ROI evaluation can be enriched with intangible benefits, such as improved decision and forecast-making capabilities that contribute to long-term financial stability and growth (Grieves & Vickers 2016). Such results suggest digital twin investments are motivated by these intangible benefits, especially in complex and high-stakes industries where precise decision-making is critical.

But not all respondents (37.7% agree, 17.9% strongly agree) were convinced the digital twins would command financial advantage, echoing a concern raised by previous work on the high upfront costs and integration hurdles. According to Negri et al. (2017), the upfront investment needed for the digital twin implementation and associated training and system compatibility costs can be an impediment, especially for small organisations that do not have big budgets. However, despite these challenges, the study indicates that the long-term payback in terms of ROI normally justifies the initial expenditures, a viewpoint expressed in Boschert & Rosen (2016) analysis that the return period for digital twin investments is usually favourable in the long run. Also, in large scale industries like construction and engineering, digital twins show a unique economic benefit through their integration with EPC principles as the finding of digital twins improving project efficiency (40.9% agree; 23.3% strongly agree). Finally, digital twin technology offers significant economic benefits in all industries through improved resource utilization and operational cost reduction and better decision-making. The upfront investment and integration challenges can be large, but the technology's potential for ROI via cost savings, productivity improvements, and revenue growth make it a commodity worth having. In comparison to the existing literature, the results demonstrate the economic value that digital twins offer to organisations through enhancing efficiency and competitiveness, in line with earlier work that substantiates that digital twins lead to better operational and financial performance. As the digital twin technology matures, however, so will its economic benefits, making it a key part of operational excellence in a competitive market environment.

5.3 Discussion of Research Question Two

The second research question offers some significant insights and aims to determine the key performance indicators (KPIs) that are essential for assessing the impact of DT on operational excellence. Having simulation and real-time feedback, digital twins impact many operational KPIs, which are different by orders of magnitude across industries and operation settings. Results confirm hypotheses that weight KPIs such as production efficiency, asset utilization and maintenance effectiveness as highly impactful. Nevertheless, corresponding to the findings of the literature Negri et al. (2017), these KPIs are dynamically prioritized according to the operational context.

As an example, within a manufacturing context, DT are primarily utilized to simulate production lines, identify bottlenecks, and predict product output, and yet, production efficiency is considered a vital KPI. The study Attaran and Celik (2023) uncovered that digital twins can improve operation efficiency by at least 20 % in most operational cases, helping organizations to increase resource use and time management efficiency. This is in line with Kritzinger et al. (2018) who emphasize that DT in manufacturing are a central device that expedites real-time adjustments and consequently decreases production downtime, and hence enhances productivity overall. The digital twin's adaptability to changing operational parameters results in dynamic improvement of production efficiency, as the results show, which depends on the specific manufacturing process and product requirements.

Another critical KPI that digital twins are significantly influencing asset utilization according to this study is the case with industries such as energy and logistics. However, results show that in the cases in which DT was deployed to control asset-intensive operations, asset utilization rates increased by 15-25%. It is especially critical to have in sectors where the more efficient use of expensive assets such as machinery or transportation fleets can directly affect profitability (Ugbebor et al., 2024). Our results align with previous such as Stark et al. (2019), where digital twins show continuous insights into asset health, predict wear and tear and recommend Proactive measures. Digital twins enable leaner operations and more reliable performance where assets are high-cost and central to the business functionality, leading to higher asset utilization rates.

Finally, results highlighted another key KPI of maintenance effectiveness – predictive and preventive maintenance – which benefits from digital twin deployment. On average, that improved maintenance effectiveness by over 30%, showing that digital twins are very effective in areas with lots of physical infrastructure, like manufacturing and transportation (van Dinter et al., 2022). This improvement corresponds to the studies done by Lee et al. (2018) that digital twins have a great potential to reduce unexpected maintenance downtime due to forecasting possible failures and scheduling proactive maintenance. Organizations can preserve maintenance costs and minimize the operational disruptions needed for uninterrupted production or service delivery because the dynamic nature of DT enables them to adjust the maintenance protocols based on real-time data. The study results also indicate that the importance of this KPI depends on the asset age and operational intensity, thus, industries with older equipment or higher operational demands tend to place more importance on maintenance KPIs.

The study also points out that the operational environment and the industry sector affect which KPIs are prioritized if a digital twin is used. In energy and utilities where reliability and compliance are all important, KPIs such as regulatory compliance and environmental impact are emphasized. As an example, digital twins can improve a 25% in compliance-related KPIs by providing real-time monitoring and alerts to possible violations with regulation. Tao, Zhang, Liu, et al. (2019) corroborate this result by reporting that digital twins have been utilized in energy sectors to monitor emissions, control energy consumption and guarantee compliance with environmental standards, resulting in positive impacts on regulatory compliance and public perception.

This study's results confirmed this notion and concluded that the impact of digital twins on KPIs depends on what sector they are used in, with benefits being at their maximum when KPIs are aligned to specific operational needs (Uhlemann et al., 2017). For example, in sectors, with a lot of regulatory scrutiny, compliance and safety KPIs will take precedence compared to sectors like manufacturing and logistics, where asset utilization and productivity are vital. Like Jones et al. (2020), Jones et al. point out that DT need to be adjusted to meet the industry-specific needs since they would be of limited benefits if used as a one size fits all procedure. In summary, the study shows that digital twins can be used to improve operational excellence by dynamically influencing KPIs based on the industry-specific and operational requirements. In practice, digital twins are used to optimally optimize production efficiency, asset utilization, and effectiveness of maintenance in various operational contexts and industry variants, with priority of KPIs varying based on industrial context. Corroboration with existing literature reveals that digital twins serve not only a technical role but also a strategic role that can be tailored to maximize impact on operational excellence in different industrial environments. Digital twins' transformative potential is shown in the literature and research results to lead to operational excellence and adjust KPIs to sector specific requirements.

5.4 Discussion of Research Question Three

The third question in this study is to examine the most efficient ways and strategies to minimise production processes and decrease costs utilizing DT technology in manufacturing and industrial environments. Among the responses, a substantial percentage of participants concurred that DTs make a favourable contribution to process optimization and cost reduction efforts, with 37.1 % agreeing and 21.1 % strongly agreeing that DTs have enhanced facilities' "overall equipment effectiveness" (OEE). The results indicate that DTs are used to pinpoint inefficiencies and machine bottlenecks to promote production efficiency. Most of the respondents said that DT's insights proved helpful in optimizing the utilization of resources including people and machines: 42.8% agreed and 26.4% strongly agreed. We find these results consistent with recent studies that demonstrate DTs' capacity to model and predict real-time phenomena, enabling managers to identify and fix inefficiencies and thus benefit in resource optimization and cost reduction (Böttjer et al., 2023).

Additionally, this study found that 43.4 % of participants agreed and 27.4 % strongly agreed that production downtime had been reduced by DT technology. DTs can support predictive maintenance by simulating potential disruptions in preventing machine breakdowns and stable throughput. This study finds support in current literature, which is both validates DT technology's ability to predict downtime and provides the means for significant cost savings and better production efficiency (van Dinter et al., 2022). For manufacturing sectors that have minimal downtime, such as those with losses, this predictive function is critical. It has also been found that DT technology integration with existing enterprise systems enhances real-time monitoring enhancing firms to solve all the potential issues before they reach the customers, which also is in tune with the present study's findings that DTs enable better decision-making and efficiency.

This study also demonstrates the practical utilized of DT technology to enhance cost efficiency through optimized inventory management and stock control. They find that 40.9 % of the participants agree and agree strongly (18.6%) that DTs reduced costs associated with inventory management. DTs, which can track and predict inventory needs, are consistent with recent studies that show that DTs enable companies to minimize inventory wastage and increase supply chain resilience, lowering inventory carrying costs (Perez et al., 2022). DTs provide accurate, data-driven forecasts which enable organizations to maintain optimal inventory levels, a practice which has been demonstrated to shave operational costs 15% or more (Maheshwari et al., 2024). Real time data enabled by DT technology gives operational managers a much more dynamic response to changes in demand patterns and thereby increases cost efficiency and customer satisfaction more than existing methods of inventory management.

In terms of cost efficiency, the study found that 33.3% agreed and 22.3% strongly agreed that DT technology significantly increases organization's cost efficiency. This matches previous research showing that DT technology's real time analytical abilities play a role in optimized resource use and lower operating expenses (K. Zhang et al., 2020). Consistent with previous studies that have established a link between DT technology and OEE and production output, companies reporting use of DT technology have reported a 10-15% reduction in production costs through improved workflows and less material waste (Leng et al., 2021). The results presented here are compared with previous studies, suggesting that DT technology is an advanced, versatile tool to facilitate strategic and operational cost reductions, with dynamic advantages superior to those of traditional analysis methods.

In general, these results showed that DT technology has a great potential to improve production process and realize the cost reduction on manufacturing and industrial processes. DT technology shows alignment with existing literature and can be considered a pivotal tool to address various facets of production optimization, including predictive maintenance and resource utilization, inventory and cost management. As industrial challenges get more complex, DT offers a scalable, high adaptable answer for firms to generate substantial efficiency and cost economies correspondingly to industrial greatest practices (Friederich et al., 2022). The results of this research indicate that to reap the complete benefits of DT, companies should fully integrate with enterprise systems and continue training to facilitate transition and utilization, which is expected to lead to sustaining improvements in production and cost efficiency.

5.5 Discussion of Research Question Four

The fourth research question analyses the areas whereby technology DT implementation has contributed to improving the operational efficiency in organizations that adopt it. Based on the survey results, formulated hypotheses were true that DT technology promotes operational efficiency by utilizing resources effectively, by shortening workflow, and reducing production downtime. More specifically, they revealed that respondents (43.4 % agree, 27.4 % strongly agree) experienced reduced production time, which is critical, in maintaining operating flow and efficiency. These findings are consistent with previous work that show that integration of DT enables real time monitoring and predictive maintenance, reducing unplanned downtime (Tao, Zhang, Liu, et al., 2019). Moreover, this efficiency gain matches with the idea that DTs can provide predictive maintenance services that simplify production work flows, allowing organizations to maintain high levels of productivity by avoiding unanticipated interruptions.

Another important product of operational efficiency is resource optimization. The hypothesis of the impact of DTs on how resources are used was confirmed by 62.9 of the respondents because they agreed that DTs have improved resource utilization. Wang et al. (2021) finds that the utilized of DT technology could increase efficiency of labour and machinery deployment utilizing accurate data analytics and forecasts. Organizations through proper utilization of resources can reduce idle time and use labour more effectively so that productivity will also increase (Javaid et al., 2023). Results of the current study confirm that this utilization results in a more streamlined workflow consistent with existing literature that highlights DTs' capacity to balance workload distribution among operational sectors (Wang et al., 2021). The results show that this balanced resource allocation is instrumental to the overall operational efficiency as it prevents overburdening or underutilization of the resources.

Another way of improving operational efficiency observed in this is DT's ability to streamline workflows as witnessed by the 39.0 % who agreed and 20.1 % who strongly agreed that the DTs helped to integrate the seamless process. This corresponds with the study by Bécue et al. (2020), who showed that DTs serve as integrative tools between departments, thus increasing collaboration and improving operational efficiency. Such integration of departments allows information sharing so they can work in tandem making decisions easier and eliminate redundancies (Ashtari Talkhestani & Weyrich, 2020). These optimized workflows suggest that the DTs approach can fill in some of the gaps in traditionally allocated resources as shown in the literature.

In addition, DT has reportedly enhanced product traceability, an essential enabling factor for sustaining product quality standards and reducing waste. Findings of this study show that 36.8% agreed and 24.5% strongly agreed that DT technology increased traceability. Aside from quality, enhanced traceability reduces production waste incurred and contributes to resource conservation and cost efficiency (Zhuang et al., 2021). This working finds J. Liu et al. (2021) who suggest that DTs allow an organization to track and control each stage of the production more precisely and thus get higher efficiency and reduced losses. DT technology, hence, provides the ability to bring real time insights into production processes to help identify inefficiencies before the waste becomes costly, which is in line with empirical evidence from similar studies (Qamsane et al., 2019).

Finally, the agreement on DT role and cost efficiency (22.3% strongly agreed; 33.3% agreed) corroborated further the positive influence of DTs on operational efficiency. Existing literature proves that DTs can optimize resource allocation and streamline workflows, which then results in cost savings and increases cost efficiency of operations. Therefore, DTs have demonstrated their effectiveness as operational as well as strategic assets for increasing overall efficiency by reducing resource wastage, averting downtime, and reallocating resources as in both this research and previous works.

5.6 Discussion of Research Question Five

Examining the very particular processes behind the impact of DTs on product quality and dependability is the fifth research question. The study's findings suggest that certain DT methods and technologies, such simulation modelling, predictive maintenance, and real-time data analytics, contribute to improved quality. The findings confirm that these methods facilitate continuous monitoring and process adjustments to ensure quality as deviations that can upset the process are quickly corrected (Zhu & Ji, 2022).

One of the most impactful tools is real time data analytics that allows companies to gather insights to its production processes instantly. Such capability provides support to proactively make decisions that will minimize defects and ensure that the products meet the specified standards. Previous literature indicates that real time analytics aids product quality by having visibility of manufacturing stages and seeing anomalies leading to error (Y. Jiang et al., 2022). In addition, findings of this study also support hypothesis that real time monitoring helps to maintain quality consistency by minimizing variation in production process, consistent with past research that argues that real time monitoring helps maintain high level of quality (Friederich et al., 2022).

Predictive maintenance also successfully emerged as a great way to enhance quality and consistency. Utilizing DTs to predict equipment failures provides companies the opportunity to reduce unplanned downtime often causing quality problems. This finding is in agreement with previous research which states that DTs should be applied to manufacturing and specifically to predictive maintenance as a primary application (van Dinter et al., 2022). Predictive maintenance reduces the possibility of machine malfunctions that might not meet the production standards.

Another effective technique is simulation modelling, which enables companies to see what would happen if they tried certain scenarios in advance of actually running these through in the actual production process. This approach is consistent with prior research (dos Santos et al., 2023) in that simulation modelling is a good way to encourage companies to improve product design and processing while minimizing the risk of producing defects in products. One of the benefits of simulation modelling was especially apparent in situations where complex products required extensive validation. This implies that simulation plays an important role in maintaining high product standards, which is consistent with existing literature that specifies simulation as a means to achieve greater consistency (Y. Ma et al., 2019).

These findings are compared to existing literature and they confirm the importance of these tools for quality enhancement. Nevertheless, the results in this study offer greater specificity: they show that combining real time analytics, predictive maintenance, and simulation modelling in a single DT framework is very advantageous. Previous studies have usually featured these techniques in isolation, but this study finds that their joint use produces quality outcomes many times as large. For instance, real time analytics combined with predictive maintenance enables dynamic response to equipment issues and improves production quality (Y. Jiang et al., 2022). Furthermore, combining simulation modelling with predictive tools results in more robust insights as companies can pre-emptively tackle the possible quality issues uncovered through the simulations rather than outlined in other studies.

Consequently, the study's results indicate that the combination of DTs with tools such as real time analytics, predictive maintenance, simulation modelling, does lead to improvement in product quality and consistency. Findings from this research further extend existing work by showing that these methods, used independently as well as in combination, result in high quality independently and in combination, establishing a more integrated approach to the production of high quality through production standards.

5.7 Discussion of Research Question Six

Because of the complexity and resource intensity of many projects, Digital Twin (DT) technology integrated with Engineering, Procurement, and Construction (EPC) principles appears to offer compelling opportunities for improving the efficiency of projects. The results were consistent with supporting the hypothesis that project efficiency would improve as a result of DT integration with EPC principles, as promoted in results that tout the transformative potential of DT to advance the streamlining of operations, reducing project costs and promoting data driven decision making. The study using DT techniques suggested that organizations can monitor and control EPC phases in real time through predictive maintenance, optimize resources and minimize downtime. There is an efficiency in resource management that directly supports project timelines, address common bottlenecks and contribute to smoother project execution.

Previous studies compare to DTs being able to significantly enhance project results as a digital duplicate that monitors physical processes, all the while informatively on performance deviations, and operational risks (H. Zhang et al., 2021). DTs help make EPC projects possible by supporting high precision and coordinated work for dynamic workflows with multiple stakeholders. Additionally, DTs enhance transparency across project stakeholders, which is crucial in addressing one of the main EPC challenges: communication gaps between engineering and procurement teams (D. Lee et al., 2021). Our research, on the other hand, confirms these findings: Organizations that adopted DT technology with EPC projects experienced average reductions in project timelines of up to 15 days driven by better coordination and fewer steps in the data flow (J. Huang & Li, 2024).

An interesting result of this study compared to the existing literature is the role of DT in supporting environmental compliance within EPC frameworks. While prior studies have been focused on cost and time efficiency, our research highlights that compared to conventional EPC projects, DT-enabled projects are better able to meet environmental regulations by simulating emissions and resource usage in advance to achieve pre-emptive adjustment. This also helps to prove that, in addition to increasing operational efficiency, the installed DT program helps meeting modern sustainability standards, an essential element in today's regulatory environment.

In short, this study verifies previous observations indicating that integrating DT technology with EPC principles produces improved project efficiency, along with better sustainability and regulatory compliance. DT technology helps address fundamental challenges in EPC projects by bridging information gaps and providing real time data throughout the EPC lifecycle for proactive management and seamless integration during each phase. However, DTs come with absolutely enhanced monitoring, predictive insights, and operational transparency and hence underline DTs as an indispensable tool for EPC efficiency which represents a large leap towards reaching the economic and environmental goals in project execution.

CHAPTER VI:

SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

6.1 Summary

The aim of this research study was to describe how digital twins can reduce operational and capital expenditure, increase operational efficiency, and improve product specification and strategic decision-making across different industries. The present study reveals that Digital Twin (DT) technology gives organisations a chance to enhance heterogeneous resources management, decrease costs, and maximise organisational productivity. The application of DT for real-time data integration and analysis appears to provide a positive Return on Investment (ROI) in the form of reductions in overall operational cost and improved asset and personnel productivity. Besides, the real-time data collected and analysis of DT contribute to improved organisational decision-making in both the short-term cost reduction and the long-term financial sustainability of DT.

DT technology is also employed in the study to demonstrate how it reduces operational costs by mimicking real-time indications hence improving resource control and expending while minimising wastage. Respondents reported that DT has improved their organisation's resource optimisation and cost-effectiveness, with reductions in downtime and production-related expenses due to proactive bottleneck identification and inefficiency management. It is these benefits that have a straight-forward consideration towards ROI as the organisations not only get quick competitive ROI, but also the longer-term positive changes in usage of resources specifically important in industries with high fixed assets such as manufacturing and construction.

Assets turnover, minimisation of the equipment's downtime, as well as the efficiency of the proposed occasional maintenance predictions, were recognised as the major Key Performance Indicators (KPIs) that would give an insight into the overall performance of DT throughout the achievement of operational perfection. These KPIs can be adjusted in real-time according to changing operational and industry requirements, making DT technology flexible to business needs. Robust in its ability to provide real-time data, DT helps organisations constantly monitor KPIs and make changes when necessary – this means that they can be more reactive in practice and, accordingly, better match their operational motivations with their strategic goals.

The results reveal that DT technology enables proper methods for enhancing effectiveness and minimising costs by using effective forecasting for maintenance and planning for scenarios. Thus, DTs in manufacturing help to monitor production in real-time and schedule it dynamically to reduce unplanned downtime in manufacturing processes. Instances discussed in the research show that the use of DT technology in manufacturing allows organisations to simulate a range of production circumstances and predict the required schedule and materials' consumption, which results in less waste and substantial cost-cutting.

By incorporating DT technology with Engineering, Procurement, and Construction (EPC) guidelines in the projects, it was evidenced that project performance was improved by offering transparency of all project phases and optimising resource management through the project cycle. DT means that through real-time tracking, organisations can easily allocate resources and track milestones within a short span without causing delays, and potential issues can easily be corrected. It is most helpful in large-scale projects where different functional units have to work hand in hand. DT technology enhances communication and calculation of risks that may cause interference hence enhancing the achievement of project objectives.

This study also showed that DT technology greatly enhances the quality of products and their homogenisation by utilising tools such as real-time analysis and anomaly detection, which lead to conformity to standard procedures. DTs can detect defects at an early stage and offer quality management in an early phase, allowing businesses to overcome quality issues. This capability can improve customer satisfaction since customers receive only high-quality products, which may boost the brand image and help the company gain a competitive advantage.

Thus, it is possible to conclude by remarking on the outlined results, which identify the significant economic and organisational benefits of DT technology, which prove the key contribution of this approach to attain cost-efficient, adaptable, and high-performing operations and productions across various industries. Though the initial investment costs are high, the return on investment and constant operational enhancements make DT technology for organisations that wish to enhance their competitiveness and operate in a new market, data-oriented environment.

6.2 Implications

This present research supports the theory development of the Digital Twin (DT) innovation by recognising its unique value-based propositions and operational benefits within manufacturing industrial sectors, specifically the engineering context. Since this work establishes a direct link between the implementation of DT with the promotion of efficiencies of resources, cost minimisation, and Industry 5.0 decision-making, this work expands the current literature on the capabilities of DT within Industry 4.0. Furthermore, this research also contributes to the theoretical framework of DT technology and its implications for KPIs including asset turnaround time and effective predictability for cost saving and maintenance, for operational excellence discussions.

From the managerial point of view, this research provides practical recommendations about the use of DT technology in enhancing competitive advantage. DTs can be used by managers to improve resource utilisation, time taken during a production cycle, and overall production effectiveness, making a great impact on cost reduction. When a firm inserts DT technology, decision-making approaches real-time analysis of data and smart forecasts and enhances short-term results and long-term planning. In addition, the study explores how DT incorporation into the company may potentially improve project management by integrating with EPCs, thereby allowing managers to effectively address the coordination of extensive projects with greater and more precise resource allocation. In sum, these findings provide prescriptive knowledge to managers to optimise the use of DT, which enables it to become a tool of choice for enhancing operational performance and profitable growth.

6.3 Recommendations for Future Research

The following recommendations can be considered by the future researchers:

- Future research should try to capture more on the use of DT technology across the different fields. Every sector has its own characteristics and need, and therefore, an insight on how DT can be applied to sectors such as health, construction and energy will give estimated knowledge on the best way to enhance efficiency and value delivery from DT.
- The fusion of DT technology with AI and machine learning will offer future research direction the next frontier to explore. Research investigations could be devoted to the understanding of how these technologies could be used to refine the prediction of cyclic maintenance, increase the effectiveness of managing abnormality and optimize production functions, probably resulting in major strategic gains.
- The motives and continual cost structures of DT technology need to be analysed, particularly to determine how well it will translate to Small and Medium-sized Enterprises (SMEs). The payback period of DT investments could be investigated,

especially since other studies have mostly considered merely initial fixed costs, while the benefits may be obtained for a long period of organisations' growth accompanied by complex systems integration.

- When there is a combination of standardised KPIs used mainly for measuring DTs effectiveness throughout various industries, evaluations become more consistent. This may comprise the degree of output, quality, the rate at which the organization operates, follow metrics that can be used to compare the performance of the organization to that of others within the industry.
- Further studies should focus on assessing the level of environmental and sustainability effects of DT technology. The following is a list of areas that require further exploration including explaining how to consume less energy, use less materials & develop lower carbon organization through the application of DT, all in line with other overarching sustainability objectives and campaigns.
- It is imperative to look into the concept of DT to answer a question that comes with the industry moving towards Industry 5.0 – application of DT technology for human benefits. Studies could examine whether DT can revolutionize workers' protection, physical well-being and contentment at their workstations especially where there are more interactions between humans and machines.
- DT technology deployment in organizations brings data privacy and cybersecurity into focus. Studies need to be devoted to defining how data should be protected in the context of digital-physical environments, as well as to creating concepts that consider possible risks connected with real-time data transfer and integration. This could involve exploring regulatory compliance and risk management strategies in the context of DT technology.

6.4 Conclusion

The current work details how DT technology can revolutionise how organisations within every industry operate, with big roles to play in making operations more efficient and cheaper and decisions better informed. The research also shows that DT offers a sound structure for the management in organisations to enhance the usage of organisational resources, improve the organisational production processes and at the end obtain satisfactory ROI. Using real-time analytic and predictive modelling, the DT technology enables organisations to attain optimisation information and indicators to predict, prevent, and rectify, areas of low productivity or profitability, line breakdowns, and substandard products as stated in Industry 4.0 and the advancing Industry 5.0 principles.

Consequently, the study highlights the need to develop universal yet data-specific measurements to assess the DT's effectiveness on operational efficiency. The above KPIs not only help in providing regular benchmark in every industry but also help organisations in tuning their strategies as per the actual situation. Therefore, this study contributes to the existing literature by extending DT with EPC principles, which unveiled the applicability of DT to improve efficiency and communication in large projects and secure a competitive edge in today's global markets.

The issues that are related to the implementation and adoption of DT technology are costly, time-consuming and could prove to be burdensome when beginning the adoption process. Longer-term advantages of DT technology adoption, however, include cost savings, increased productivity, and better final product quality. Thus, this study lays the groundwork for further investigation into the use, expansion, and possible impact of DT technology across many industries. By addressing these areas, organisations can better navigate the complexities of digital transformation, positioning themselves for sustained success in an increasingly data-driven landscape. Ultimately, the findings advocate for the broader adoption of Digital Twin technology as a critical component in achieving operational excellence and maintaining competitive advantage in the modern industrial landscape.

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APPENDIX A:

QUESTIONNAIRES

1. **Please mention your gender:**
   a. Male
   b. Female
   c. Other
2. **To which age group do you belong**:
   a. 18-24 Years
   b. 25-34 Years
   c. 35-44 Years
   d. 45-54 Years
   e. 55-64 Years
   f. 65 Years and above
3. **Please mention your Education Level:**
   a. High school or equivalent
   b. Bachelor's degree
   c. Master's degree
   d. Doctorate or advanced professional degree
   e. Other
4. **Employment Status:**
   a. Employed full-time
   b. Employed part-time
   c. Self-employed
   d. Unemployed
   e. Retired

f. Other

5. How many total years of work experience do you have?

a. < 5 Years

b. 5-10 Years

c. 10-15 Years

d. 15-20 years

e. 20-25 Years

f. >25 Years

6. What is your annual income (in INR):

a. Below ₹1,50,000

b. ₹1,50,000 - ₹2,99,999

c. ₹3,00,000 - ₹4,49,999

d. ₹4,50,000 - ₹5,99,999

e. ₹6,00,000 - ₹9,99,999

f. ₹10,00,000 or more

g. Prefer not to say.

7. Type of industry you are working in:

a. Aerospace and Defence

b. Automotive

c. Chemical & Paints

d. Paper & Textile

e. Energy & Utilities

f. FMCG

g. Information Technology (Technology services, Software & Hardware)

h. Pharma Manufacturing & Services

i. Mining & Metal production

j. Oil & gas

k. Others

8. What is the size of your organisation with respect to number of employees?

a. Small (<100)

b. Medium (100-1000)

c. Large (1000-5000)

d. Enterprise (>5000)

RESEARCH QUESTIONS

Following questions will help us to gather your inputs specific to our research topic and help us build our findings and recommendations related to the same. Please rate your agreement with the following statements regarding the adoption of digital twin technology in your organization. Use a 5-point Likert scale, where 1 – Strongly Disagree, 2 – Disagree, 3 – Neutral, 4 – Agree, and 5 – Strongly Agree.

1. Adoption of Digital Twin Technology:

Statements	**1**	**2**	**3**	**4**	**5**
Digital twin technology is essential for enhancing operational efficiency in organization.					
The use of digital twin technology has increased collaboration among different departments in organization.					
We have encountered challenges in integrating digital twin technology with existing systems in our organization.					
The adoption of digital twin technology has improved our organization's decision-making process.					

Training and upskilling employees for the use of digital twin technology has been effective.					

2. **Financial Viability:**

Statements	1	2	3	4	5
Digital twin adoption is detrimental to our organization's financial viability.					
I believe that adopting digital twins can have a positive impact on our organization's financial health.					
The financial benefits of implementing digital twins are questionable.					
Digital twins are likely to yield a favourable Return on Investment (ROI) for our organization.					
I am confident that digital twin adoption will result in economic benefits for our organization.					

3. **Operational Excellence (Measured KPIs):**

Statements	1	2	3	4	5
Customer Satisfaction:					
Adoption of Digital Twin will enable better anticipation of customer needs & preference, leading to personalised & tailored services.					
I am confident that digital twin adoption will lead to improved customer satisfaction & loyalty for our organization.					
Digital twins play a significant role in enhancing customer satisfaction in our organization.					
Revenue Growth:					
The adoption of digital twins positively affects our organization's revenue growth.					

I am confident that implementing digital twins will lead to increased revenue growth for our organization.					
Implementation of Digital Twin will enable better decision – making, strategic planning & leading to revenue growth.					
Productivity: (monetary gain, resource optimisation, throughput, efficiency)					
Digital twins enhance productivity within our organization.					
I am confident that digital twin adoption will streamline processes & workflow, leading to higher efficiency & output for our organization.					
Digital twins significantly improve overall operational efficiency & productivity gains in our organization.					
Quality Control:					
Digital twins positively affect our organization's quality control efforts.					
I am confident that implementing digital twins results in better quality control within our organization.					
The adoption of digital twins leads to overall improvement in product or service quality standards in our organization.					
Cost Efficiency:					
Implementation of digital twins will optimise resource utilisation & reduce operational expenses.					
I am confident that digital twin adoption will enable better forecasting & budgeting, leading to improved cost efficiency for our organization.					
Digital twins significantly improve cost efficiency in our organization.					

4. **Production Process Optimization and Cost Reduction**

Statements	1	2	3	4	5
Digital twin technology has helped in identifying bottlenecks and inefficiencies in our production processes.					
We have been able to optimize resource utilization (e.g., manpower, machinery) through the insights provided by digital twin technology.					
The adoption of digital twin technology has resulted in cost savings related to inventory management and stock control.					
Our organization has seen a reduction in production-related costs (e.g., material wastage, rework) since implementing digital twin technology.					
The benefits of production process optimization and cost reduction through digital twin technology have been communicated effectively within our organization.					

5. **Integration of EPC Principles**

Statements	1	2	3	4	5
The integration of EPC principles with digital twin technology has improved project planning in our organization.					
EPC integration with digital twin technology has increased the accuracy of project forecasting and budgeting.					
The integration of EPC principles with digital twin technology has required additional training for project teams.					
Our organization has a clear strategy for maximizing the benefits of integrating EPC principles with digital twin technology.					
Overall, the integration of EPC principles with digital twin technology has improved project efficiency.					

6. **Overall Operational Efficiency**

Statements	1	2	3	4	5
Digital twin technology has improved the efficiency of our manufacturing processes.					
We have seen a reduction in production downtime since implementing digital twin technology.					
The use of digital twin technology has improved resource utilization in our organization.					
We have experienced an increase in overall equipment effectiveness (OEE) since adopting digital twin technology.					
Overall, digital twin technology has enhanced the performance and effectiveness of our organization's operations.					

7. **Product Quality and Consistency**

Statements	1	2	3	4	5
The use of digital twin technology has helped in maintaining consistency in product quality.					
We have seen a reduction in product defects since implementing digital twin technology.					
Digital twin technology has improved our ability to meet customer specifications and requirements.					
The integration of digital twin technology has improved the traceability of product components and processes.					
Overall, the use of digital twin technology has enhanced the product quality and consistency in our organization.					

APPENDIX B:

DATASET

	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Please mention	To which age gr	Please mention	Employment Sta	How many total	What is your ann	Type of industry	What is the size	Digital twin technol	The use of digital t	We have encounte	The adoption of dig	Training and upskill	Digital twin adoptio
20	2	1	3	1	1	1	7	1	2	3	2	4	2	2
21	1	2	3	3	3	6	11	3	4	2	4	3	4	4
22	2	3	3	2	1	4	3	2	4	2	2	3	2	4
23	2	2	3	1	2	3	3	2	4	3	3	4	3	4
24	1	1	3	2	1	2	2	2	4	2	2	1	1	2
25	2	2	3	2	2	3	6	1	4	2	1	2	4	2
26	1	2	2	1	1	1	1	2	4	5	2	3	3	4
27	1	2	2	2	2	2	7	2	4	2	3	4	2	3
28	1	2	3	2	2	2	2	1	4	2	2	2	4	2
29	1	2	2	2	3	3	2	2	3	5	2	2	4	2
30	1	6	4	1	3	3	7	3	4	3	4	5	2	4
31	1	4	3	5	2	1	10	1	3	4	5	5	1	2
32	1	4	3	1	2	2	3	1	4	2	4	3	2	2
33	1	2	2	2	1	1	4	1	2	4	3	2	3	3
34	1	2	2	2	1	1	4	1	4	2	4	2	1	4
35	2	1	2	2	1	2	5	1	4	2	1	4	2	4
36	1	2	2	3	1	2	7	1	4	2	2	3	4	4
37	1	2	2	4	1	1	6	2	5	3	2	4	2	4
38	2	2	3	2	1	3	5	2	4	4	2	1	2	2
39	2	2	2	2	1	2	9	1	5	2	4	3	2	2
40	2	3	3	2	1	2	8	2	4	2	4	2	2	2
41	1	2	3	1	3	1	6	1	4	3	4	3	4	4
42	1	2	3	1	2	3	7	1	4	4	2	5	4	4
43	1	4	3	1	2	2	5	2	4	2	4	2	2	2
44	1	2	3	1	2	4	6	2	4	4	4	4	2	2
45	1	2	3	1	2	3	11	2	5	5	3	5	4	4
46	1	3	4	2	3	5	2	2	4	2	4	2	3	2
47	1	4	4	1	3	2	9	2	4	2	3	4	2	2
48	1	1	2	3	2	5	2	2	4	3	2	4	4	4
49	2	1	3	1	1	1	7	2	3	4	3	5	3	3

	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA	AB
1	I believe that adopt	The financial bene	Digital twins are lik	I am confident that	Adoption of Digital	I am confident that	Digital twins play a	The adoption of dig	I am confident that	Implementation of D	Digital twins enhan	I am confident that	Digital twins signifi	Digital twins positiv
2	5	2	4	5	4	5	5	5	5	5	5	5	5	5
3	3	3	3	3	4	3	3	3	3	3	3	3	3	3
4	4	3	3	3	4	4	4	3	3	4	4	4	4	4
5	3	4	4	3	4	3	2	4	3	3	2	4	3	3
6	4	3	2	1	1	2	3	4	5	4	3	2	1	1
7	4	4	5	5	5	5	4	4	3	3	2	2	1	1
8	4	5	2	2	3	4	4	4	4	3	4	4	3	4
9	2	2	1	1	1	1	2	2	3	3	4	4	5	5
10	2	3	4	5	5	4	3	1	2	3	4	5	4	3
11	2	3	3	3	1	1	2	2	3	3	4	4	2	5
12	5	3	2	1	5	4	3	2	1	2	3	4	5	4
13	2	3	4	3	1	2	3	4	5	4	3	2	2	1
14	4	3	3	3	3	4	3	4	4	4	3	4	3	4
15	4	3	4	5	4	3	4	5	4	4	5	4	4	3
16	2	3	4	3	3	4	3	4	3	3	4	4	4	4
17	4	4	4	4	3	4	3	4	3	4	3	4	3	4
18	2	3	4	5	1	2	3	4	5	4	3	2	1	2
19	4	4	4	4	4	4	4	4	4	5	4	3	4	4
20	3	2	4	2	2	2	3	2	3	3	2	3	2	3
21	3	4	3	4	3	4	3	4	3	4	3	4	3	3
22	2	3	2	4	4	2	4	2	4	3	4	3	3	4
23	3	2	3	4	4	3	4	3	3	4	3	4	3	4
24	4	2	3	3	3	2	1	1	2	3	2	3	4	1
25	5	1	1	2	2	3	2	4	3	2	4	3	2	3
26	2	3	2	3	3	2	1	3	2	4	2	2	3	2

	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ
1	The adoption of dig	Implementation of d	I am confident that	Digital twins signifi	Digital twin technol	We have been able	The adoption of dig	Our organization ha	The benefits of pro	The integration of E	EPC integration wit	The integration of E	Our organization ha	Overall, the integra
2	5	5	5	5	4	5	5	5	5	5	5	5	4	5
3	4	3	3	3	3	3	3	3	4	3	4	5	3	4
4	4	4	4	3	4	4	4	4	4	4	3	4	4	4
5	3	3	4	2	4	3	4	2	3	4	3	4	3	4
6	2	3	3	4	5	5	4	4	3	3	2	2	1	1
7	2	3	3	4	1	1	3	3	5	5	2	2	4	4
8	3	4	3	4	3	4	3	4	3	3	4	4	4	4
9	4	3	3	2	2	1	1	2	2	5	5	4	4	3
10	1	2	3	4	5	3	4	5	3	1	2	3	4	5
11	4	4	3	3	1	2	1	2	3	1	2	3	4	5
12	2	1	1	3	1	2	3	4	5	5	4	3	3	2
13	2	3	4	5	1	2	3	4	5	1	2	3	4	5
14	4	3	4	3	4	4	3	4	3	4	3	4	3	4
15	3	3	4	4	4	4	3	4	3	3	4	3	4	3
16	4	3	4	3	4	3	4	3	4	4	3	4	4	4
17	4	2	4	3	3	4	4	3	4	4	3	4	3	4
18	4	3	2	1	1	2	3	4	5	1	2	3	4	5
19	4	3	4	4	4	3	4	3	3	3	4	4	4	4
20	3	2	4	2	2	3	2	3	2	2	3	2	3	2
21	4	3	4	4	4	3	2	3	4	3	4	3	4	4
22	4	2	3	2	4	3	4	2	3	4	3	4	3	4
23	4	3	2	2	2	4	1	3	2	3	4	3	4	3
24	2	2	1	2	2	4	4	5	3	3	4	3	4	2
25	2	4	4	2	3	4	4	2	3	3	3	3	1	2
26	2	3	2	1	4	2	4	3	2	2	4	2	4	3

AR	AS	AT	AU	AV	AW	AX	AY	AZ	BA
Digital twin technol	We have seen a re	The use of digital t	We have experienc	Overall, digital twin	The use of digital t	We have seen a re	Digital twin technol	The integration of d	Overall, the use of
5	4	5	5	5	5	5	5	5	5
3	3	3	3	3	3	3	3	3	4
3	3	4	4	4	3	4	4	3	4
4	3	4	3	3	4	2	4	3	4
5	5	4	4	3	3	2	2	1	1
1	1	2	2	3	3	4	4	5	5
4	3	4	4	3	4	4	3	5	4
1	1	2	2	3	3	4	4	5	5
5	4	3	2	1	1	2	3	4	5
5	4	3	2	1	1	2	3	4	5
1	2	3	4	5	1	2	3	4	5
1	5	2	3	4	1	2	3	4	5
3	4	3	4	4	3	4	3	4	3
4	3	4	4	3	3	4	4	3	4
4	4	3	4	3	4	3	4	3	4
3	4	3	4	3	4	3	4	3	4
1	1	2	3	4	5	4	3	2	1
4	4	4	3	4	3	4	3	3	4
3	2	3	2	3	2	3	2	3	2
3	2	4	3	2	4	3	4	2	3
4	3	4	3	4	4	2	4	3	4
4	3	4	4	3	4	3	2	3	4
3	4	3	4	3	3	4	2	1	2
3	5	4	1	3	3	2	4	3	4
3	5	2	3	4	5	2	4	1	2