MSc in Business Administration & E-Business

Integrating Digital Twins into Offshore Wind Turbines: A Systems and Stakeholder Perspective

Samuel Ziak (163854)

Standard page count: 69

Supervisor: Carsten Sørensen

Submission Date: 15th of November 2024

Declaration

I hereby declare that the work presented in this thesis is the result of my own independent research.

Samuel Ziak

Full Name Goes Here (Candidate)

15 / 11/2024

Date

Abstract

Objective: This research explores the integration of digital twin technology within the offshore wind industry, focusing on its impact on organizational processes, stakeholder engagement, and value perception. It also aims to evaluate the role of digital twins in extending turbines' operational lifespans and identify key challenges related to data interoperability and system integration.

Methods: A qualitative research approach was employed, utilizing semi-structured interviews with 15 key stakeholders, including engineers, project managers, and operational managers. Swanson and Ramiller (1997) used the Organizing Vision framework to interpret how digital twin technologies are conceptualized and integrated into the organizational processes. Data analysis involved reflexive thematic analysis to identify core themes around stakeholder perceptions, challenges, and the technological benefits of digital twins.

Results: The findings indicate that stakeholders perceive digital twins as critical for improving operational efficiency, particularly through predictive maintenance, real-time monitoring, and data-driven decision-making. However, significant challenges, including data interoperability, high implementation costs, and data security concerns, were identified as barriers to adoption. While most stakeholders recognize the technology's potential, a minority remain skeptical due to the extended timeline for realizing a return on investment.

Conclusion: Digital twin technology has transformative potential in the offshore wind sector by enhancing operational efficiency and promoting stakeholder collaboration. Nonetheless, addressing interoperability and data security challenges is crucial for broader adoption. The research provides a foundation for optimizing digital twin deployment strategies and highlights the need for further technological development to fully capitalize on their capabilities.

Keywords: digital twins, offshore wind, predictive maintenance, data interoperability, stakeholder engagement

Acknowledgments

This thesis would not have been possible without the invaluable support of my supervisor, Carsten Sørensen at CBS. Like a lighthouse guiding a ship through rough seas, his expertise and clear direction helped navigate the complexities of my research, ensuring I stayed on course and remained motivated throughout the process. I am also deeply grateful to Azam Nadir, Ulf Tygesen, and Michael Jepsen from the partnering company. Your insights were the compass points that guided my work, providing practical perspectives that enriched the content and depth of this thesis.

A special thanks goes to Arne Rahbek, who initially opened the door for me at the company. Your belief in my potential was the first spark that set the journey in motion, laying down the foundation stones for both my professional growth and this research. Much like planting and nurturing a seed over time, your support has helped me grow into the field I am passionate about.

I owe everything to my parents, Anna and Tibor, who have supported my journey from Slovakia despite the distance. You have been the roots anchoring me as I've grown and stretched my branches in Denmark. Your unwavering encouragement, love, and belief in my abilities have given me the strength to weather any storm.

I would also like to acknowledge my close friends, Lukas Benus and Robert Seidner, who embarked on the same path of pursuing an MSc degree. Walking alongside you both has been like having companions on a long hike; your presence made the journey more manageable and more rewarding. Our camaraderie provided motivation and strength, reminding me that we are not alone in this pursuit.

Finally, to my best friend and girlfriend, Sofia Gheno, your patience, love, and unending support have been the constant sunshine that motivated me to persevere. You've been there through the highs and lows, providing a listening ear and a warm smile, making even the most challenging days feel lighter. I am deeply grateful for your presence in my life, as it has been the greatest source of joy and inspiration throughout this journey.

Table of contents

Contents

List of Acronyms

Acronym	Meaning
DT	Digital Twin
GW	Gigawatts
TW	Terawatts
NASA	The National Aeronautics and Space Administration
IS	Information Systems
IT	Information Technology
IoT	Internet of Things
CD-ROM	Compact Disc Read-Only Memory
LCD	Liquid-crystal Display
GPS	Global Positioning System
IIoT	Industrial Internet of Things
CPS	Cyber-Physical Systems
USD	U.S. dollar
ML	Machine Learning
TLS	Transport Layer Security
H-VAWT	H Vertical Axial Wind Turbine
OpenFAST	Software-engineering Framework
SIMA	Structure Integrity Manager
BO	Bayesian Optimization
LSTM	Long Short-term Memory
EEMD	Ensemble Empirical Model Decomposition
DTSense	Digital Twin Sense
RUL	Remaining Useful Life
IGBT	Insulated-Gate Bipolar Transistor
SIL	Software-in-loop
HIL	Hardware-in-loop
ADRC	Active Disturbance Rejection Controller
O&M	Operation & Maintenance
SCADA	Supervisory Control and Data Acquisition
BIM	Building Information Modelling
R&D	Research & Development
5G	Fifth-generation technology standard for cellular networks
MW	Megawatts
DOF	Degree of Freedom
FEM	Finite Element Model
NIB	Nonlinear Integral Backstepping
DDPG	Deep Deterministic Policy Gradients
MFC	Model-free Control

Raspberry Pi	a series of small single-board computers
SAP	System Applications and Products in Data Processing
ECC	Enterprise Central Component
AR	Augmented Reality
SHM	Structural Health Monitoring
DDM	Data-driven Models
ROI	Return on Investment
AI	Artificial Intelligence
ERP	Enterprise Resource Planning
OEM	Original Equipment Manufacturer

List of Tables

Chapter 1: Introduction

1.1 Opening Section

Imagine navigating a vast ocean without a compass or map; each wave brings uncertainty, and the destination remains unclear. The offshore wind sector faces a similar scenario as it navigates the complex waters of global sustainability goals. The world's urgent drive to meet the targets of the Paris Agreement, particularly achieving net zero carbon dioxide emissions by 2050 (Global Wind Energy Council 2024), requires industries to innovate and adapt rapidly. Offshore wind energy, a promising solution within this transformation, must overcome technical and operational challenges to realize its full potential.

In this evolving landscape, digital twin technology could act as the compass, providing real-time insights and predictive capabilities for offshore wind farms. Digital twins (DT, this and any other acronym can be seen in the list of Acronyms) are advanced digital replicas of physical assets, allowing stakeholders to monitor, simulate, and optimize operations in previously unimaginable ways (Javaid, Haleem, and Suman 2023). However, the question remains: How effectively can this technology be integrated into the offshore wind industry, and how do stakeholders perceive its value and impact?

This study explores the integration of digital twins within the offshore wind sector through the lens of Information Systems theories. By examining how this technology influences organizational processes, stakeholder engagement, and overall project efficiency, the research aims to provide insights that align technological innovation with global sustainability goals. The chapter outlines the study's objectives and lays the roadmap for the following sections, setting the stage for a detailed analysis of the background, problem statement, and research objectives.

1.2 Background

The energy sector is transforming, driven by the urgent need to meet the Paris Agreement's net zero carbon dioxide emissions target by 2050 (Global Wind Energy Council 2024). Central to this transformation is adopting renewable energy technologies, particularly wind energy, which is increasingly viewed as a vital component of achieving global sustainability goals. The recent COP28 summit underscored this emphasis by setting an ambitious target to triple global renewable energy capacity to 11,000 gigawatts (GW) by 2030 (Global Wind Energy Council 2024). This target aims to accelerate the deployment of wind and other renewable technologies. However, despite these optimistic projections, current policies and implementation rates suggest that we may only reach two terawatts (TW) of installed wind capacity by 2030, falling short of the global goal required to limit global warming to 1.5°C (Global Wind Energy Council 2024)

Digital twin technology, initially conceptualized by NASA for space missions, has emerged as a powerful tool in various industries, including offshore wind energy (Allen n.d.). Digital twins provide real-time, digital replicas of physical assets, enabling continuous monitoring, predictive analysis, and operational optimization (Javaid, Haleem, and Suman 2023). For the offshore wind industry, where environmental and logistical challenges significantly increase operational costs, digital twins offer a solution to enhance the efficiency and longevity of wind turbines (Rinaldi, Thies, and Johanning 2021). Maintenance costs alone can constitute up to 15% of a wind farm's revenue, and the ability to predict and prevent failures through digital twins could substantially reduce these expenses (Rinaldi, Thies, and Johanning 2021).

Despite the promising potential of digital twins, the offshore wind sector faces challenges related to their integration. Issues such as interoperability, data security, and stakeholder engagement remain critical barriers. Moreover, much of the existing literature focuses primarily on the technical aspects of digital twins, leaving a gap in understanding how stakeholders across different levels perceive their value and interact with this technology. This research addresses these gaps by examining digital twin integration through the lens of Information Systems. It comprehensively explains their impact on organizational processes and stakeholder collaboration in offshore wind projects. This study contributes to the broader discussion within Information Systems (IS) and offers practical insights for optimizing digital twin technology to align with global sustainability objectives.

1.3 Statement of the Problem

This study intends to investigate how to anchor the concept of a digital twin within the information systems debate. To explore the integration of digital twin technology within the offshore wind industry, focusing on organizational-level impacts, stakeholder engagement, and perception of value. The development of offshore wind farms necessitates developing and integrating advanced technologies. This viewpoint provides an institutional perspective on adopting and diffusing new technologies within companies. It also demonstrates how businesses learn how to structure and manage processes associated with innovation in information systems (Swanson and Ramiller 1997). The research aim of this study is:

"To explore the integration of digital twin technology within the offshore wind industry, focusing on organizational-level impacts, stakeholder engagement, and perceptions of value."

The study seeks to provide deeper insights into how digital twins influence organizational processes, facilitate stakeholder collaboration, and support long-term strategic goals in offshore wind projects by addressing this aim. It also highlights the challenges of implementing and scaling these technologies across different project stages.

1.3.1 Research Gap

Despite the growing adoption of digital twin technologies in various industries, there still needs to be a gap in understanding how offshore wind stakeholders perceive their value. Most existing studies focus on the technical aspects of digital twins (LeBlanc and Ferreira 2020, Branlard et al. 2020, Xiangjun et al. 2020, Li et al. 2024), often overlooking the human element: how stakeholders engage with and benefit from these innovations. Additionally, there is insufficient exploration of the organizational challenges that arise from integrating digital twins, particularly concerning interoperability and long-term adoption across different lifecycle stages of offshore wind projects.

1.3.2 Research Question

To address these gaps, the following research questions were developed to guide the investigation:

Primary question: "*How do different stakeholders perceive value creation provided by implementing digital twins in offshore wind.*"

Sub-questions:

- SQ1: How do stakeholders perceive the needs and value of digital twins in the context of offshore wind?
- SQ2: What are the expectations, roles, and needs of critical stakeholders in the deployment of digital twin technology?
- SQ3: What are the main challenges related to the adoption of digital twins in the offshore wind?
- SQ4: How do digital twins serve as catalysts for organizational transformation across the different stages of offshore wind farm projects?

1.3.3 Research Objectives

In line with the research questions, the following research objectives were formulated to ensure a structured approach to the investigation:

- RO1: To evaluate stakeholder perceptions regarding the needs and value of digital twins in the context of offshore wind energy projects.
- RO2: To identify and analyze the expectations, roles, and needs of critical stakeholders in the deployment of digital twin technology within offshore wind projects.
- RO3: To assess the main challenges associated with the adoption of digital twin technology in offshore wind projects.

- RO4: To explore how digital twin technology facilitates organizational transformation throughout the lifecycle of offshore wind projects, with a particular focus on interoperability challenges.

These objectives are designed to systematically address the research gap, ensuring the study is comprehensive and focused. Upon the project's conclusion, the degree of achievement of the research aim and objectives will be reflected, and any unmet goals will be examined.

1.3.4 Justification of the problem

While digital twin technology has been increasingly adopted in industries like aerospace, manufacturing, and even closer industries such as oil and gas, there needs to be a greater understanding of how it creates value in the offshore wind sector (Wanasinghe et al. 2020). The perspectives of stakeholders affected by utilizing digital twins are crucial in determining the success of its adoption. However, most existing studies focus primarily on the technical performance of digital twins in an individual component of an offshore wind turbine, overlooking how different stakeholders perceive and engage with these technologies. This leaves a significant gap in understanding how stakeholder expectations, needs, and roles influence the success or failure of digital twin implementations in offshore wind projects.

Moreover, more research must explore the organizational transformation driven by digital twins, particularly across different stages of offshore wind projects, from development to long-term operations. Understanding these stakeholder-driven and organizational aspects is essential for optimizing digital twin technology's integration and long-term success as the industry scales.

This study attempts to fill this research gap by conducting a reflexive thematic analysis of 15 stakeholders involved in work on offshore wind projects. The investigation focuses on how stakeholders perceive the value creation provided by digital twins and how these technologies influence organizational processes and decision-making in the offshore wind industry.

1.4 Rationale

The rationale for this study emerges from the urgent need to enhance offshore wind turbines’ efficiency and operational lifespan by applying advanced technologies. Offshore wind energy plays a crucial role in achieving global sustainability goals; however, it faces significant challenges, particularly in maintaining and optimizing turbines that operate under harsh marine conditions. Maintenance costs can account for up to 15% of a wind farm’s revenue, highlighting the necessity of solutions beyond monitoring to extend the operational life of these assets (Rinaldi, Thies, and Johanning 2021).

This research investigates how digital twin technology can be effectively integrated within the offshore wind industry to optimize turbine performance and extend operational duration. By examining the organizational and stakeholder perspectives, the study seeks to understand the broader implications of digital twins beyond their technical capabilities. Specifically, the research will evaluate digital twins' impact on turbines' operational longevity, analyze stakeholder perceptions, and identify barriers to interoperability and data security. These objectives are designed to provide practical insights into how digital twins can be aligned with the long-term sustainability goals of the offshore wind sector.

Furthermore, this study contributes to the broader field of Information Systems by exploring the integration of digital twins through a systems and organizational lens. Understanding how digital twins influence technical performance, stakeholder engagement, and decision-making processes is crucial for successful adoption. The research provides evidence-based recommendations for optimizing digital twin deployment strategies by addressing these aspects. The findings aim to bridge the gap between technological innovation and its practical application, ultimately supporting offshore wind projects' economic viability and sustainability.

1.5 Scope

The scope of this study focuses on the application and integration of digital twin technology, specifically within the offshore wind sector. The research narrows its examination to the digital twin technology used for monitoring and optimizing individual components of offshore wind turbines or, in some cases, an entire turbine. It extends its focus to only some wind farms or the broader energy grid, including components like cables, substations, and other interconnected infrastructure. This limitation is set to ensure depth rather than breadth in the analysis.

Geographically, the study focuses on offshore wind farms in Europe, a region experiencing rapid expansion in offshore wind capacity and where technological innovation, especially in digital twins, is being increasingly explored. This region is chosen based on its significant role in the global renewable energy market and the widespread adoption of offshore wind technology. However, while policies supporting offshore wind and digital twins are relevant to the industry, they are outside the scope of this research.

The study's time frame focuses on contemporary advancements in digital twin technology over the past five years (2019-2024). However, for the theoretical frameworks and foundational concepts applied in the research, such as Shoshana Zuboff's work on the smart machine and Swanson and Ramiller's frameworks, the study extends further back in time. This approach is taken to provide a comprehensive understanding of the evolution of technology and its foundational theories.

While the study does not cover every stakeholder involved in offshore wind project development, it explicitly investigates the perspectives of engineers, project developers, and operational managers, who play critical roles in adopting and implementing digital twins within organizations. This limited focus reflects the constraints of examining predominantly one company.

Thematically, the research targets three primary areas: (1) the impact of digital twins on the operational lifespan and efficiency of individual turbine components, (2) the challenges associated with integrating these technologies, particularly in terms of interoperability and data security, and (3) stakeholder perceptions regarding their value. Broader topics, such as the influence of digital twins on overarching energy policy or their application outside the offshore wind sector, fall outside the scope of this thesis, ensuring a focused and in-depth investigation.

1.6 Significance

The significance of this research lies in its dual contribution to theoretical understanding and practical application within the offshore wind sector. Academically, the study addresses a gap in the literature by exploring the integration of digital twin technology from an organizational and stakeholder perspective rather than focusing solely on technical aspects. This investigation offers a deeper understanding of how digital twins not only optimize the operational lifespan of offshore wind turbines but also influence decision-making, stakeholder collaboration, and strategic planning. By grounding the research within the Information Systems framework, the study builds on and extends existing theories, such as Swanson and Ramiller's (1997) Organizing Vision framework and Zuboff's (1988) Theory of the Smart Machine, to demonstrate how digital twins drive organizational transformation and innovation in renewable energy.

Practically, this research provides actionable insights for the offshore wind industry, which is under significant pressure to meet global sustainability goals and maximize the efficiency of wind farms (Global Wind Energy Council 2024). The study's findings are valuable for companies seeking to implement digital twin technology effectively, highlighting the challenges and benefits of integrating these systems into existing workflows. By examining interoperability, data security, and stakeholder engagement, the research offers a comprehensive guide for organizations looking to optimize turbine performance and extend operational life, ultimately contributing to offshore wind projects' long-term economic viability and sustainability.

Furthermore, the research identifies strategic opportunities for leveraging digital twins beyond monitoring capabilities, focusing on predictive maintenance and real-time decision-making. This emphasis not only aligns with the broader industry goal of reducing operational costs but also supports the vision of expanding the role of digital twins in transforming offshore wind operations. By providing a foundation for future studies to build upon, this research opens new pathways for exploring the socio-technical impacts of digital twins, contributing to a more sustainable and efficient energy sector.

1.7 Structure of the Document

A concise summary of each chapter´s purpose is described in this section. Introduction The chapter presents the industry's background and the rationale behind the research problem. In addition, it outlines the scope and significance of this research. The literature review chapter synthesizes existing literature about the golden thread of this study. Furthermore, as an alternative, the literature review chapter identifies gaps in the present body of knowledge. It explains how this research fills one of them—followed by the Methodology Chapter, where the goal of this chapter is to make sure that the objectives and research questions are in line. After this, the Results Chapter aimed to review the primary data about this study's research aims, goals, and questions. In other words, the primary data source for this study's main subject was a set of 15 online recorded interviews that were later transformed into codes and themes. Interpretations of the Results Chapter are analyzed in the Discussion Chapter. Finally, the Conclusion Chapter describes the findings and the study's limitations. Following that, the Conclusion Chapter will highlight the study's contribution from the standpoint of research and ultimately wrap up the research.

Chapter 2: Literature review

2.1 Introduction

The chapter showcases recent research in information systems, theoretical frameworks, digital innovation, offshore wind, digital twins, its subsequent stakeholders, and values. The literature review draws on technological and technical literature; most of the material is taken from the literature on information systems and engineering. Furthermore, this chapter comprehensively reviews the existing literature on digital twin technology within the context of the offshore wind energy industry. The primary focus is understanding how digital twins can enhance operational efficiency, stakeholder engagement, and organizational transformation.

The chapter begins by discussing the theoretical foundations that inform the study, with each framework contributing to understanding how digital twins are adopted and applied within the offshore wind sector. This is followed by exploring the evolution and classification of digital twin technology and examining its specific applications within the industry. The review also addresses the role of different stakeholders in the value-creation process, focusing on their perceptions of the derived benefits of digital twins. In addition, the literature identifies several challenges that hinder the adoption of digital twins. These include technical issues such as interoperability, high implementation costs, and data management in extreme environments.

This chapter integrates diverse academic perspectives to lay the conceptual foundation for the research. It highlights existing gaps in the literature and sets the stage for the following methodological and empirical analysis.

2.2 Digitization

2.2.1 Digital Innovation

Digital innovation is creating new products by creatively combining digital and physical components. According to current research, most IS research has been done on process innovation instead of product innovation (Swanson 1994 cited in Yoo (2010)). Digitization—converting analog information into digital formats—allows for novel combinations. This process also compels firms to reevaluate their organizational structure and IT infrastructure, making physical objects programmable (Fichman 2004, Yoo, Henfridsson, and Lyytinen 2010).

With the rise of platform business models over the past few decades, the emphasis has shifted from traditional vertical integration to a flatter, more innovation-centric approach to value creation. Platforms connect individuals, groups, and resources through technology, creating an interactive ecosystem where value can be generated and exchanged (Gawer 2009 cited in Zachariadis and Ozcan 2017). Yoo et al. (2010) describe digital platforms as layered, modular information technology infrastructures that operate within business networks. Research indicates that digital platforms provide the socio-technological framework needed by platform owners and complementors—such as developers—to pool resources and skills, collectively producing valuable derivatives like applications. The digital infrastructure serves as the value delivery architecture, linking members of a value network (Alstyne, Parker, and Choudary n.d., Tiwana, Konsynski, and Bush 2010, Yoo, Henfridsson, and Lyytinen 2010).

2.2.1.1 Digital Objects and Their Nature

Within this intricate digital ecosystem, the elements that constitute these platforms - often called digital objects - play a crucial role. Digital objects exist in various forms (Hui 2016, Yoo, Henfridsson, and Lyytinen 2010). They are " data and metadata regulated by structures or schemas that take shape on a screen or hide in the back end of a computer program." Even everyday objects like microwaves and thermostats have computing capabilities integrated through the Internet of Things (IoT), while others remain entirely digital, such as media files (Yoo, Henfridsson, and Lyytinen 2010). According to Yoo et al. (2012), these digital products acquire new affordances, altering user experiences and reshaping traditional industry boundaries (Baskerville, Myers, and Yoo 2020).

Fundamentally, digital objects are non-material bitstrings (Faulkner and Runde 2013). They exist as a series of bits (0 and 1) regardless of their function. Software generates these objects using hardware, such as computers, smartphones, or sensors embedded in other devices, to execute written instructions (Baskerville, Myers, and Yoo 2020) . Intangible entities and physical "bearers" like Compact Disc Read-Only Memory (CD-ROMs), flash drives, or Liquid-crystal display (LCD) panels are the only means for human agents to interact with them (Faulkner and Runde 2013).

2.2.1.2 Computed Nature of Digital Objects

Digital objects are continuously computed. To exist, they must execute instructions—an essential feature of digital objects. This computation has two significant implications. Firstly, it means digital objects can be reprogrammed. The software executes instructions to create these objects, which can be modified, replaced, or deleted based on these instructions (Yoo, Henfridsson, and Lyytinen 2010). The specific computer system architecture does not affect this; imperative, declarative, or dynamic learning instructions ultimately shape digital objects (Baskerville, Myers, and Yoo 2020).

Secondly, the software performs pre-formatted, automatic, and contingent actions that give rise to digital objects (Kitchin and Dodge 2014). This blurs the line between digital things and digital actions. For example, an account balance is often computed as needed rather than stored as a static record, reflecting its status as a dynamic digital object created by an algorithm. Similarly, every time a user views a photo on a smartphone, it results from a fresh execution of the same set of instructions. Digital objects, therefore, emerge from live actions carried out by algorithms that interact with material and non-material elements. (Baskerville, Myers, and Yoo 2020)

2.2.1.3 Application of Digital Objects in Practice

For instance, consider a vehicle equipped with the Google Maps navigation system. When the car is in motion, a global positioning system (GPS) sensor captures and digitizes the vehicle's position data. Google receives this digital object, which includes the vehicle's location and other relevant information. The data is manipulated and returned as a visual representation—a blue dot—on the vehicle's display. This digital object moves in sync with the car, illustrating how digital objects are computed representations that correlate with physical entities (Baskerville, Myers, and Yoo 2020).

2.2.2 Industrial Transformation

Industrial transformation refers to the processes through which industries experience behavioral shifts driven by emerging technologies. These transformations are essential for enhancing organizational operations, improving customer relationships, and managing dynamic market conditions. Organizations adopting these changes remain relevant and continuously advance (Yaqub and Alsabban 2023).

Industry 4.0, a German government initiative presented in 2011 at the Hannover Fair, exemplifies such transformation (Xu et al. 2021). It is propelled by the Industrial Internet of Things (IIoT) and Cyber-Physical Systems (CPS), which use computer-based algorithms to manage and monitor physical assets like vehicles, robots, and machinery. For the wind farm industry, adopting Industry 4.0 technologies—such as digital twins, big data, machine learning, and the Internet of Things—is crucial for automating, monitoring, and analyzing supply chains efficiently. One of the capabilities of Industry 4.0 is comprehensive control over a product's entire lifecycle, from initial design to end-of-life, incorporating consumer feedback into subsequent versions. In this context, digital twin technology emerges as a pivotal tool, enabling the efficient management and optimization of complex systems.

However, data sharing and system interoperability challenges become apparent as the wind farm industry embraces these advancements. Multiple stakeholders, including project developers and local communities (Salimbeni, Redchuk, and Rousserie 2023), are involved in the construction and management of offshore wind farms, each utilizing unique communication methods and data storage "languages." This lack of a typical "language" slows data exchange, adversely affecting production. Thus, seamless interoperability across organizations is crucial for Industry 4.0 to be fully realized in sectors like offshore wind farms. Defined as the ability of computer systems or programs to exchange information and perform tasks efficiently and accurately, interoperability remains a significant hurdle, particularly in the context of digital twin frameworks for offshore wind farms (Ambarita et al. 2024).

In the offshore wind energy sector, digital twins are gaining traction due to their ability to address challenges unique to offshore operations, such as location, environmental conditions, and maintenance. These virtual models are invaluable for continuously monitoring and managing offshore wind farms, which are often challenging, time-consuming, and costly to access and service (Jari Kaivo et al. 2020, Wurm et al. 2023).

2.3 Digital Twins

Digital twins are virtual replicas of as-built objects or actual processes and events that mimic these objects in terms of behavior throughout their lifecycle. They use current information, historical data, and specific simulation models for the physical objects they represent (Ambarita et al. 2024). The significance of digital twins in various industries is becoming increasingly evident, with the market anticipated to grow from USD 10.1 billion in 2023 to USD 110.1 billion by 2028. This represents a compound annual growth rate of 61.3% (MarketsandMarkets 2023). Appendix B.1, derived from Statista, visualizes the growth trajectory of the digital twin market from 2020 to 2025 across industries. The data shows that the manufacturing sector leads this growth, followed by substantial increases in the energy and utilities sector, where the value is expected to rise from $0.34 billion to $3.83 billion (BIS Research. 2020). These statistics highlight the exponential growth and potential applications of digital twin technology.

2.3.1 What Is a Digital Twin

Digital twins have several fundamental and imperative components that ensure their functionality and relevance. According to Valk et al. (2022) , the elementary components include the physical component (e.g., a jet engine or an offshore wind turbine), its virtual digital counterpart, and the information flow between these components, which could be one-way or two-way. These components form the backbone of digital twin technology, facilitating the representation and analysis of physical entities in digital space.

Sharma et al. (2022) identified several imperative components to enhance the effectiveness of digital twins. These include IoT devices that collect sensor data from physical assets, ensuring a high-fidelity connection for accurate data transmission. Data management systems then gather and process this data to monitor system behavior and provide inputs for machine learning systems. Machine Learning (ML) algorithms make predictions, provide feedback, and identify mitigation strategies in exceptional situations, optimizing the digital twin's performance. Additionally, robust security protocols are necessary to protect the integrity of the information flow between these components. Performance evaluation metrics are also crucial, allowing for ongoing assessment of the digital twin's accuracy and resilience.

The continuous stream of operational and environmental data collected from the physical asset through sensors maintains the coherence and accuracy of the digital model. This constant data flow ensures that the digital twin remains an up-to-date reflection of the physical entity it represents. The connectivity module integrates the digital twin with other systems through IoT and cloud computing services, enabling real-time communication and seamless data exchange (Svendsrud and Paparova 2023).

2.3.2 Applications of Digital Twins in the Offshore Wind Industry

Digital twins have become crucial in the offshore wind sector, addressing the unique challenges of offshore operations, including remote locations, harsh environmental conditions, and complex maintenance processes. These virtual models provide real-time monitoring and predictive analysis capabilities, significantly reducing turbine downtime and enhancing turbine durability through advanced pre-failure predictions. By implementing these strategies, digital twins help lower repair costs and improve the overall reliability of turbines (2020). Additionally, they allow for performance optimization by dynamically adjusting turbine operations to align with fluctuating environmental conditions, thereby maximizing energy output and operational efficiency.

Digital twins substantially benefit offshore wind projects' planning and construction phases. They allow for accurate modeling of wind farm layouts and turbine configurations in a digital environment before physical implementation. This approach minimizes the risk of costly post-installation modifications. It ensures that wind farms are designed to comply with site-specific environmental conditions, optimizing their layout and performance from the outset (Osmundsen, Meske, and Thapa 2022, Schleich et al. 2017).

Using digital twins in the offshore wind industry economically reduces costs. Transport Layer Security (TLS), for instance, ensures secure data transmission between digital twin components, which is critical for maintaining data integrity in such applications. By optimizing maintenance procedures and reducing the need for on-site inspections, digital twins help lower operational expenses—crucial for offshore installations, where maintenance logistics are incredibly challenging due to the vast distances and scale of offshore platforms (Enders and Hoßbach 2019, Jiang et al. 2021).

From an environmental perspective, digital twins also support sustainability initiatives by reducing the need for physical interventions, thereby minimizing the environmental impact associated with offshore maintenance activities. This aligns with the broader sustainability objectives inherent in wind energy delivery, making digital twins a pivotal contributor to environmentally responsible energy production (Batty 2018, Liu et al. 2021, Shen, Wang, and Deng 2021).

Digital twins are also instrumental beyond operational and maintenance phases, particularly in training and innovation. They enable the simulation of extreme conditions and complex scenarios, enhancing workforce readiness and equipment durability. Additionally, as digital twins integrate with advanced machine learning models, they continuously improve predictive accuracy, helping optimize the performance and longevity of wind turbines (Wurm et al. 2023, Ciuriuc et al. 2022). Below is a summary table showcasing the different phases a digital twin can be applied to.

Stage	Application of Digital Twins	Key Benefits	References
Design & Construction	Modeling complex layouts and configurations of wind farms accurately in digital space before physical implementation.	Reduces the need for costly post-installation modifications; ensures optimal compliance.	(Osmundsen, Meske, and Thapa 2022, Schleich et al. 2017)
Operational Management	Real-time and predictive analysis for maintenance, adjusting turbine operations based on environmental conditions.	Enhances durability, reduces maintenance costs, and improves reliability of turbines.	(Jiang et al., 2021)
Maintenance & Repair	Predicting failures and determining maintenance needs through advanced analytics and data integration.	Lowers operational costs, minimizes downtime, and improves efficiency.	(Enders & Hoßbach, 2019; Jiang et al., 2021)
Performance Optimization	Adjusting turbine behavior dynamically to match changing conditions, analyzing performance data for optimal energy production.	Increases energy output and operational efficiency.	(Batty 2018, Liu et al. 2021)
Environmental Monitoring	Using digital twins to monitor the impact of wind farms on local ecosystems, particularly marine environments.	Facilitates sustainable practices and compliance with environmental regulations.	(Batty 2018, Liu et al. 2021, Shen, Wang, and Deng 2021)
Innovation & Training	Employing digital twins for training scenarios, simulation of extreme conditions, and continuous improvement through machine learning models.	Enhances workforce competence, ensures readiness and durability of equipment.	(Wurm et al. 2023, Ciuriuc et al. 2022)

Table 1 Stages and Applications of Digital Twins in Offshore Wind (own work)

2.3.3 Classification of Digital Twins Based on Their Application

As previously indicated, offshore wind farms can use digital twins for various applications. It makes it possible to predict and simulate how various variables affect offshore wind turbine performance. The digital twin is constantly updated with real-time data from wind farms for condition monitoring and control, enabling operators to make educated judgments and modifications without being physically present. The invoked time-series data can be utilized to estimate power output and anticipate possible problems in conjunction with machine learning methods. The table below illustrates the four viewpoints used to categorize the digital twin idea based on differences in application: modeling, estimate and control, monitoring, and prediction. Digital twins are mainly employed for modeling and estimating in the early phases and then for regulating, monitoring, and predicting in the latter stages. It should be noted that the use of digital twins in offshore wind farms extends beyond the parts of the turbine, such as the rotor and blade, and includes the complete system, including the pitch angle control, mooring system, gearbox, bearing, support structure, and powertrain. Furthermore, depending on the application and components under consideration, different definitions of digital twins are applied in offshore wind farms (Ambarita et al. 2024).

Main purpose	Applications	Sources
Modelling	H vertical axial wind turbine	LeBlanc and Ferreira (2020)
	Turbine blade	Chetan et al. (2021); Sahoo et al. (2017)
	Fatigue re-assessment on structure	Tygesen et al. (2018)
Estimation	Wind turbine loads	Branlard et al. (2020 b)
	Wind speed	Hu et al. (2021); Li and Shen (2022)
	Mooring life tension	Walker et al., (2022)
	Remaining useful time of gearbox	Mehlan et al. (2022); Moghadam et al., (2021)
	Remaining useful time of power converter	Fang et al. (2018); (Jahanshahi Zeitouni et al. 2020)
Monitoring	Gearbox	Xiangjun et al. (2020); Wadhwani et al. (2022)
	Uncertainties of structural dynamics	Augustyn et al. (2021); Ebrahimi (2019)
	Turbine substructure	Grosse (2019)
	Mooring system	La Grota et al. (2021)
	Wind turbines (farm)	Pargmann et al. (2018); Fahim et al. (2022)
Prediction	Wind turbine	Li et al. (2024); Iosifidis et al. (2021)
	Support structure	Wang et al. (2021); Momber et al. (2022)
	Electrical components	Oñederra et al. (2019) (Nuñez-Montoya et al. 2022)
	Gearbox	Zhao et al. (2021)

Table 2 Classification of digital twins based on their purposes (not an industry standard) (Ambarita et al., 2024)

2.3.3.1 Modelling

From a modeling perspective, to facilitate experimental characterization, LeBlanc and Ferreira (2020) provided a digital twin model of an H Vertical Axial Wind Turbine (H-VAWT). They could record intricate loading phenomena during the test procedure and update the finite element model using the Siemens Test. lab software's poly max curve filter. To anticipate turbine response for dynamic blade pitching, the term "digital twin" is defined here as a digital duplicate of a physical apparatus. Chetan et al. (2021) used the OpenFAST framework to create a multi-fidelity digital twin structural model of the turbine blade to ensure stable rotor operation and system control. Observing the rotor from design through production, testing, and operation was part of the digital twin process. Sahoo et al. (2017) developed a finite element model structural study of shear webs with a circular hole on a turbine blade to minimize material testing. In this context, "digital twin" refers to a numerical model that can accurately imitate physical behavior in each setting without requiring costly experiments. Tygesen et al. (2018) presented the digital twin model for fatigue re-assessment on wind turbine structures utilizing Structure Integrity Manager (SIMA) software to investigate and identify discrepancies between the model and the actual measurement. The authors explained the five stages of digital twin creation for offshore wind farms: wave load calibration, measurement of uncertainties, updating the finite element model, screening and diagnostics, and cumulative fatigue monitoring. In this case, the digital twin reflects the structure as it is right now, one that can be examined to forecast how it will behave in the future.

2.3.3.2 Estimation and Control

From an estimation perspective, according to Branlard et al. (2024), a digital twin in offshore wind farms is the digital equivalent of the physical turbine that uses numerical modeling and measurements from the physical turbine to follow the life cycle of the physical assets and assess the status of the turbine. Branlard et al. (2020 b) evaluated wind turbine loads using the OpenFAST framework and the Kalman filtering technique with pitch angle, generator torque, rotational speed, and tower-top acceleration measurement signals. Hu et al. (2021) used digital twins to predict wind speed time series using the Bayesian Optimization (BO) approach, long short-term memory (LSTM) neural network, and ensemble empirical model decomposition (EEMD). Li and Shen (2022) applied a set of estimators, verifiers, setters, and selectors known as DTSense to develop a unique wind speed-sensing methodology for wind turbines based on digital twin technology. In this case, the digital twin is a digital duplicate that gathers and saves operational data from physical assets using deep learning techniques to show how an IoT functions throughout its lifetime. In addition, Walker et al. (2022) improved lifetime and safety by creating a digital twin of the mooring life tension using a cutting-edge data-driven technique. For safety reasons, they built a second digital twin to anticipate the axial tension of the mooring line in the future using the already available data. The first digital twin was created to predict the behavior of the healthy system in comparison with the real one.

Furthermore, Mehlan et al. (2022) used bond graph modeling techniques to produce a digital twin of the gear stages in wind turbines, which was then used to execute virtual sensing in real time. Using fatigue damage models, the remaining usable life (RUL) of the gear and bearing components was to be estimated using this method. An RUL (remaining useful life) prediction methodology for the prognostic and diagnostic health of an Insulated-Gate Bipolar Transistor (IGBT) power converter on offshore wind turbines was developed by Fang et al.— (2018) using digital twin technology. As a tool for optimization and better decision-making, the digital twin, in this context, is a virtual version of a physical asset that stores real-time simulation data in the framework to anticipate the RUL.

From a control perspective, Parvaresh et al. (2020) used a digital twin to apply control to a variable-speed wind turbine's pitch angle control system that operates at wind speeds higher than the rated level. The authors could use software-in-loop (SIL) and hardware-in-loop (HIL) techniques in a deep-learning backstepping controller to regulate the pitch angle through a digital twin. In a different study, Zeitouni et al. (2020) enhanced an innovative adaptive controller by adding to the active disturbance rejection controller (ADRC) to assess the wind speed error and the discrepancy between HIL and SIL results for the pitch angle management of a wind turbine plant. Here, virtual assets, physical assets, and connection data that link, reflect, and control one another make up the digital twin in wind turbine systems.

2.3.3.3 Monitoring

From a monitoring perspective, to increase operational reliability and reduce operation and maintenance (O&M) expenses, Xiangjun et al. (2020) concentrated on anomaly detection of wind turbine gearboxes by combining the advantages of model simulation technology with data-driven approaches. Wadhwani et al. (2022) explored the idea of a digital twin framework to predict the failure of turbine gearboxes using updated real-time Supervisory Control and Data Acquisition (SCADA) data. Using advanced machine learning theory (Bayesian pre-posterior theory), Augustyn et al. (2021) used digital twins to track and update the uncertainties around the structural dynamics and load-modeling parameters in fatigue damage accumulation. When discussing the difficulties in creating a digital twin model, Ebrahimi (2019) strongly recommended using tools for intelligent algorithms and uncertainty to alter the digital twin platform to resemble the real one and become feasible. Grosse (2019) documented the development and advantages of the digital twin idea from Building Information Modelling (BIM) for approaches related to monitoring and inspection in wind turbine substructures. To facilitate decision-making and the creation of optimal designs, the digital twin is a crucial step in precisely and accurately evaluating the structural integrity of pre-existing structures. To lower costs, improve O&M, and boost energy output, La Grota et al. (2021) presented a Research & Development (R&D) project called MooringSense. This concept is based on control, monitoring, and digital twin technologies and pertains to the integrity management of floating offshore wind mooring systems. Pargmann et al. (2018) used digital twins to merge commercial information with technical information, such as data streams from various sensor kinds, to monitor and analyze a whole wind farm based on cloud technologies. Using a 5G Next Generation Radio Access Network, Fahim et al. (2022) suggested a machine learning-based digital twin model to monitor wind turbines, evaluate the generated power, and build a wind turbine model regarding wind speed. In this case, the digital twin is an easy-to-use model that offers all current and integrated data based on a coherent and sensible big data processing strategy, giving the user a real-time perspective and enabling the implementation of risk-based integrity management strategies.

2.3.3.4 Prediction

From a prediction perspective, Li et al. (2024) presented research on digital twins, collaborative cloud, and edge computing used in wind turbine operation and maintenance for problem diagnosis and prediction from prediction standpoint. Iosifidis et al. (2021) investigated the impact of wind turbulence and wind speed on semiconductor devices of direct-drive wind turbines that result in fatigue using real-world, 1-s wind speed data. Wang et al. (2021) examined fault identification, condition-based maintenance, and RUL prediction to investigate the offshore wind turbine support structure and prevent unanticipated damage and maintenance expenses. In this context, a digital twin is a potentially helpful tool for comprehending the mechanisms structures go through to detect faults and create a diagnosis model that helps schedule maintenance and supports decision-making processes. Additionally, Momber et al. (2022) used the digital twin idea for control monitoring and prescriptive maintenance planning of wind turbine tower surface protection systems. In 2022, Montoya et al. created a digital twin model for wind turbine failure prognosis by comparing actual data from SCADA with simulated data from software created using artificial intelligence algorithms (Nuñez-Montoya et al. 2022). To mimic the fundamental asset in preventive maintenance, Oñederra et al. (2019) discussed a medium voltage (MV) cable model of various electrical components, such as power converter, generator, and transformer, on wind farms. The utilization of copious amounts of data regarding the behavior and performance of physical assets to incorporate them into a multidisciplinary simulation inside a digital environment that permits performance prediction is known as the "digital twin" in this context (Oñederra et al. 2019). Because it connects turbines and generators to produce electricity, the gearbox is one of the most critical and dangerous components that needs to be treated carefully to avoid wear and damage. A CapsNet-based deep learning scheme for data-driven fault diagnosis for digital twins of a wind turbine gearbox, comprising single fault and coupling fault, was introduced by Zhao et al. in 2021 (Zhao et al. 2021). Using a 5 megawatts (MW) reference drivetrain, Moghadam et al. (2021) suggested a multidegree of freedom torsional model of a drivetrain system in the prediction of gearbox RUL. In this case, the digital twin is an exact yet quick-to-compute model of the system that can forecast its future behavior and update itself based on online measurements. As a result, the digital twin is used as a management tool for the life cycle management of wind farms and modeling, control monitoring, and predictive maintenance (Salimbeni, Redchuk, and Rousserie 2023).

2.3.4 Existing Digital Twin Frameworks

According to Ambarita et al. (2024), setting up a structure that makes data storage and communication across digital and physical assets more accessible is crucial to utilizing digital twins. At the same time, historical data can predict probable device failures, and recorded operational data can be used to predict physical asset behavior. Newer and more advanced devices can be developed using the data contained in the framework as a basis. This section looks at a few frameworks used in manufacturing and offshore wind farms to establish digital twins. It also looks at how these frameworks might be used in offshore wind farms, pointing out their advantages and disadvantages and how they could be modified to fit the needs of the offshore wind industry.

2.3.4.1 OpenFAST, Hardware-In-Loop (HIL) and Software-In-Loop (SIL)

To create a linear state-space model that takes into account the offshore environment and incorporates degrees of freedom (such as shaft rotation and tower-top motion) for real-time load and fatigue assessment on wind turbines, Branlard et al. (2020 b) used OpenFAST linearizations. OpenFAST is an open-source simulation framework that links wind turbines' dynamic response (fluid, control electrical system, and structural dynamics). It is a multi-physics and multi-fidelity tool. The OpenFAST framework was also employed by Chetan et al. (2021) to capture the dynamics of the turbine blade's as-build design due to different root bending moment circumstances encountered during the simulation. The ability of OpenFAST to automatically linearize an extensive range of situations, including states, inputs, and outputs, is a crucial advantage. As demonstrated by Branlard et al. (2020 a) comparing 2 degrees of freedom (DOF) and 16 DOF in a wind turbine, OpenFAST can do simulations with only a few DOF (from 2 to 30 DOF), but standard FEM (finite element model) requires a thousand DOF. This is another advantage of OpenFAST. A digital twin architecture that integrates software-in-loop (SIL) and hardware-in-loop (HIL) approaches for pitch angle management of variable-speed wind turbines was presented by Parvaresh et al. (2020). In HIL, software systems are tested using cloud-based test benches that get input from physical assets; in SIL, code is tested in a simulation environment at a lower cost. To reduce the disparity between the SIL and HIL environments, the authors suggested using a nonlinear integral backstepping (NIB) method based on deep deterministic policy gradients (DDPG) and backed by model-free control (MFC). When SIL is fully virtualized, HIL uses sensor data to simulate actual driving conditions. The authors employ SIL and HIL to ensure that controllers can function in real-time scenarios and mimic the behavior of a closed-loop system in software. Zeitouni et al. (2020) improved upon earlier work by adding to the active disturbance rejection controller (ADRC) to account for significant aerodynamic variances, drivetrain mechanical stresses, and unidentified uncertainties.

2.3.4.2 Cloud ComputingTtechnology

Cloud computing technologies were employed by Pargmann et al.(2018), Li et al. (2024) , and Fahim et al. (2022) as a digital twin architecture for offshore wind farms. Pargmann et al. (2018) collected all the data from many Raspberry Pi sensors and SCADA systems and sent it to SAP Cloud Platforms' cloud IoT interface. Additionally, the writers created a SAP Enterprise Central Component (ECC) called ZEIT cloud to house additional data about the offshore wind farm sector, external data (weather forecasts, exchange rates, bird flight patterns, etc.), and business intelligence. They contended that by employing augmented reality (AR) to show wind farm data, the edge-cloud cooperation technique could combine technical and business data into a single digital twin.

Three levels make up Li et al.'s para for real-time O&M monitoring in offshore wind farms: data source, edge computing node, and public or private cloud computing. Because the model is based on the equipment's zero component feature, continuously adjusting the simulation results is made possible by edge-cloud collaboration for operations and maintenance. Furthermore, a cloud-based digital twin framework of Microsoft Azure, aided by the 5G-NG-RAN, was presented by Fahim et al. (2022) for the study of wind farms. The study found that the cloud architecture allowed for efficient monitoring by supplying data from supervisory control and data collecting units in each wind farm turbine.

2.3.4.3 Structural Integrity Manager (SIMA)

Tygesen et al. (2018) created a digital twin for structural monitoring systems using the cutting-edge SIMA program as a digital twin framework. Using a Finite Element model based on Bayesian analysis, SIMA can update digital twins by structural behavior and carry out wave load calibration. They use SIMA to update digital twins' stiffness and mass parameters to reduce the difference between the observed and anticipated parameters. The benefit of SIMA is that it makes it possible to analyze and identify discrepancies between digital and actual measurements by directly linking digital twins with accurate measurements.

2.3.4.4 MooringSense

To develop more effective integrity management solutions for offshore wind mooring systems, Grotta et al. (La Grotta, Harris, and Da Costa 2021) presented the MooringSense concept. The digital twin version of MooringSense is a high-fidelity fully coupled model with two components: O&M data (remaining valid data, local damage calculation in chains, and mooring analysis) for decision making, and predicted loads (virtual loads prediction, synthetic rope properties update, and floater motion prediction). MooringSense demonstrated the most recent mooring system condition data and a method for lowering uncertainty in static and dynamic offshore wind farm scenarios. The benefit of the MooringSense concept is that it can be used to create a digital twin of the mooring system as well as intelligent motion sensors, structural health monitoring (SHM) systems, and control techniques for wind turbines and farms.

2.3.4.5 Data-driven Model (DDM)

Using another digital twin framework, Walker et al. (2022) employed data-driven models (DDMs) to detect long-term drifts in the mechanical response of mooring lines for offshore wind turbines. The DDM technique dynamically injects configurator model components into the model based on information retrieved from external systems, like catalog systems. By evaluating current data on input-output behaviors to forecast future axial tension of mooring lines, DDMs were utilized to enhance computationally aware real-time monitoring systems for mooring lines. By using DDMs, the framework can distinguish between two methods—the deep learning method and the conventional machine learning method—for predicting the expected behavior of the healthy system, which can then be contrasted to the real one. By removing the need for manual model component development and instead dynamically updating the model in response to changes in the catalog system, DDMs offer the advantage of enhanced efficiency while lowering costs and time to market.

All the current frameworks compiled in Table 3 are limited to addressing the data link between physical and digital assets. This allows the digital model to display the physical asset in real-time data. To implement digital twins in the context of the Industry 4.0 standard, interoperability—the capacity for accurate information exchange between the companies—and connection are necessary. Manufacturers, suppliers, and customers are only a few businesses building, running, and maintaining offshore wind farms. It is not easy to integrate, comprehend, and apply these disparate pieces of data together, even inside the same organization. Furthermore, different businesses employ various applications and a distinct "language" to refer to the same asset features (Ambarita et al. 2024).

Frameworks	Purposes	Sources
OpenFAST	Estimation	Branlard et al. (2020a), Branlard et al. (2020b)
	Modelling	Chetan et al. (2021)
HIL and SIL	Control	Parvaresh et al. (2020), Zeitouni et al. (2020)
Cloud computing technology	Monitoring	Pargmann et al. (2018), Fahim et al. (2022)
	Prediction	Li et al. (2024)
Structural Integrity Manager (SIMA)	Modelling	Tygesen et al. (2018)
MooringSense	Monitoring	(La Grotta, Harris, and Da Costa 2021)
Data-driven model (DDM)	Estimation	Walker et al. (2022)

Table 3 Digital Twin Frameworks (not a standard) developed for offshore wind farms (Ambarita et al. 2024).

2.4 Stakeholders of Digital Twins

In the case of offshore wind digital twins, the target audience would include any individuals or organizations involved or interested in deploying and using these technologies. Core perceptual actors are owners and builders of projects, managers of offshore wind stations, governmental authorities, inhabitants, and shareholders. They include suppliers of materials, suppliers of technology, and any organization involved in a social and commercial relationship with the business but not directly involved in its operations. This is because each group occupies different positions, has different requirements, and expects something different (Cimino, Negri, and Fumagalli 2019, Jiang et al. 2021).

2.4.1 Project Developers

Offshore wind farm professionals require digital twins to design and build the infrastructure of the wind farms. These technologies are expected by those who use them to furnish minute modeling and predictive capabilities with the tendency to discover problems before their emergence. Thus, by applying DT technology, developers can make proper spatial positioning of wind farms, satisfy all the legal requirements, and ultimately decrease project implementation's time and monetary cost (Hu et al. 2021, Sharma et al. 2022).

2.4.2 Operators

Management of the wind farms lies in the hands of operators who are charged with the task of running the farms daily. Their core requirement is to have an objective of instrumental tracking and controlling turbines through the digital twins. According to the operators' expectations, the digital twin shall display the actual condition of the turbines to help predict failures and avoid unnecessary outages. This capability not only enhances operational efficiency but also enhances the life span of turbines (Parmar, Leiponen, and Thomas 2020).

2.4.3 Regulators

Regulators guard the environmental and safety standards of wind farms. They require digital twins to present an unalterable view of their functions. The authorities believe that digital twins will assist in assessing the environmental consequences, compliance with safety standards, and the evaluation of the audit. Such technologies can offer regulators rich, 'real-time' data that seems to support better oversight activities, as observed by (Osmundsen, Meske, and Thapa 2022).

2.4.4 Local Communities

Offshore wind farms impact social settings among local communities. Their requirements center on avoiding harm and achieving favorable effects on the economy. People believe that digital twins guarantee the appropriate functionality and the least harmful to the surrounding environment of wind farms. Furthermore, they assume that such technologies can help engage the communities by giving concise and easily understandable information about wind projects' effectiveness and functional status (Enders and Hoßbach 2019).

2.4.5 Investors

Offshore wind farms are developed through private capital from investors and are being expanded. Their organizations need to be confident in their return on investment (ROI). Investors anticipate that digital twins will increase the financial utility of wind farms by improving functional efficiency and decreasing maintenance expenses. These technologies help investors get elaborate analyses and forecasts that are useful in decision-making for investment (Qi et al. 2018).

2.4.6 Suppliers and Technology Providers

The secondary stakeholders include suppliers and technology providers who offer the parts and technologies for the development and operation of wind farms. They require digital twins for verification and fine-tuning of the products. These stakeholders believe that through digital twins, their products will be constantly refined through feedback received from operations in the natural environment (Jari Kaivo et al. 2020, Kirchhof et al. 2020).

2.4.7 Environmental Groups

Non-governmental organizations follow up on the effects of ecologies that have resulted from offshore wind farms. Thus, they require digital twins to guarantee that the wind farms are environmentally friendly. These groups anticipate digital twins as tools that can generate precise data concerning the effects on the environment of operations and ecosystems, including the creatures of the sea. It is essential to note that this information is also very useful in lobbying for sustainable practices in the industry (Energy Institute 2023).

Table 4 highlights how each stakeholder group, from project developers to environmental groups, engages with digital twins differently based on their roles and responsibilities. It also shows the specific phases during which these stakeholders are involved and their critical expectations of the technology. It provides a comprehensive view of the diverse perspectives and priorities in adopting digital twins.

Stakeholder	Primary Role	Main Interaction with DTs	Phase of Involvement	Key Expectations	References
Project Developers	Design and build offshore wind farms	Use for modeling, predictive capabilities, and optimization of project design	Early stage: design and construction	Optimization of project time and costs	(Hu et al., 2021; Sharma et al., 2022)
Operators	Manage daily operations of wind farms	Use for real-time monitoring, predictive maintenance, and operational efficiency	Ongoing operations	Enhanced operational efficiency and turbine lifespan	(Parmar, Leiponen, and Thomas 2020)
Regulators	Ensure compliance with environmental and safety standards	Use for compliance checks, safety audits, and real-time environmental monitoring	Ongoing oversight and compliance	Accurate data for compliance and environmental safety	(Osmundsen, Meske, and Thapa 2022)
Local Communities	Monitor social and environmental impacts locally	Expect digital twins to ensure environmental safety and provide transparent information	Ongoing community interaction and monitoring	Minimal harm and maximum economic benefits	(Enders and Hoßbach 2019)
Investors	Provide financial capital and expect ROI	Use for financial analysis, ROI improvement, and decision-making	Investment decisions and ongoing financial analysis	Improved ROI and reduced operational costs	(Qi et al. 2018)
Suppliers and Technology Providers	Supply parts and technology for wind farms	Use for product verification, refinement, and feedback integration	Early stage: technology supply and ongoing refinement	Product effectiveness and continuous improvement	Jari Kaivo et al. 2020, Kirchhof et al. 2020)
Environmental Groups	Monitor environmental impacts and promote sustainability	Use for monitoring environmental effects and advocating for eco-friendly practices	Ongoing environmental oversight	Accurate environmental data and advocacy for sustainability	(Energy Institute 2023)

Table 4 Stakeholders of Digital Twins (own work)

2.5 Value of Digital Twins to Stakeholders

In the context of digital twins for stakeholders in the offshore wind industry, value refers to the tangible and intangible benefits derived from the technology. This report's values were broken into economic, operational, sustainability, and strategic values.

Digital twins bring considerable value to stakeholders in the offshore wind industry, delivering economic (Wurm et al. 2023), operational (Jiang et al. 2021), sustainability (Enders and Hoßbach 2019, Leng et al. 2021), and strategic benefits (Osmundsen, Meske, and Thapa 2022, Woitsch, Sumereder, and Falcioni 2022). Economically, digital twins support financial sustainability by improving affordability, ROI, and revenue for stakeholders, including project investors. By integrating artificial intelligence (AI) and Internet of Things (IoT) sensors, digital twins enable effective equipment tracking, which can predict faults and reduce operational costs. They also assist in modeling different project options, helping to select the most effective and resource-efficient approach, which improves budgeting accuracy and financial certainty. Operationally, digital twins play a pivotal role in optimizing asset management, forecasting inventory needs, and minimizing equipment downtime. They enable real-time condition tracking and preventive maintenance plans, reducing the likelihood of sudden breakdowns and extending equipment life. For instance, the Danish Horns Rev Offshore Wind Farm leverages digital twins to monitor turbine conditions in real-time, improving operational efficiency and reducing out-of-service periods for turbines. This proactive maintenance not only extends equipment lifespan but also contributes to the overall effectiveness of the wind farm's output. Sustainability is another area where digital twins shine, as they facilitate energy-efficient practices and help limit environmental impact. By enabling fine-tuning of operations, digital twins minimize carbon emissions and energy waste. They support optimal turbine placement and usage to harness maximum wind power, thereby ensuring a lower environmental footprint. Additionally, condition-based maintenance supported by digital twins maximizes component utilization, reducing waste and promoting sustainable lifecycle management for turbines. Strategically, digital twins provide competitive advantages by enabling companies to gain deeper insights into market trends and customer behavior, supporting flexible, data-driven decision-making. This advantage helps companies position themselves strongly within the offshore wind sector and make well-informed, risk-managed strategic decisions. The combination of these values—economic, operational, sustainable, and strategic—illustrates how digital twins empower the offshore wind industry to make cost-effective, efficient, and environmentally responsible choices, ultimately driving progress toward more sustainable energy production.

These are being implemented by providing digital twins to enable better, more effective, efficient, sustainable, and cost-effective decision-making methods for developing the offshore wind industry.

Value Type	Description	References
Economic Value	Digital twins enhance financial sustainability by improving affordability, ROI, and revenue, reducing maintenance costs through predictive maintenance, and aiding in resource management and budgeting.	(Parmar et al., 2020; Sivalingam et al., 2018)
Operational Value	Digital twins optimize operations by enhancing inventory management, reducing downtime, and improving the efficiency of equipment through real-time monitoring and preventive maintenance strategies.	(Jiang et al., 2021)
Sustainability Value	They support sustainable practices by optimizing energy use and reducing carbon emissions and improving turbine positioning and utilization for efficient energy production and lifecycle management.	(Enders & Hoßbach, 2019; Leng et al., 2021)

Strategic Value	Digital twins provide strategic advantages by enhancing market insight, flexibility, and detailed risk analysis, supporting decision-making in competitive environments, and demonstrating commitment to innovation.	(Osmundsen et al., 2022; Woitsch et al., 2022; Batty, 2018)

Table 5 Value of Digital Twins to Stakeholders (own work)

2.6 Challenges of Integrating Digital Twins

Integrating digital twins in the offshore wind presents several technical and institutional challenges. Technologically, the reliability of digital twins is heavily dependent on secure and accurate data inputs, which must be resilient against harsh marine environments. The costs of implementing digital twins - such as acquiring sensors, data processing devices, and necessary software - can be prohibitive. Maintaining data integrity under severe weather conditions can also lead to increased operational costs and occasional data loss. These issues reflect the demanding environmental conditions faced by offshore wind farms, where consistent data collection is crucial for the effective functioning of digital twins.

From an institutional perspective, the governance of digital twins is complex, involving compliance with stringent safety, environmental, and data privacy regulations. These regulatory frameworks add complexity, particularly as they intersect with local, national, and international governance structures. Furthermore, societal acceptability must also be considered in the design and deployment of digital twins. Technical decisions must balance environmental protection with energy production, and governance must ensure a fair distribution of benefits, as outlined by (Künneke et al., 2015).

A significant difficulty lies in the practical implementation of digital twins, which often needs to catch up on their theoretical development. Previous studies have focused more on categorizing academic papers and developing theoretical models, with less emphasis on real-world applications. This gap is partly because digital twins are highly domain-dependent and rely on various technologies, making it difficult to conceptualize a universally applicable, detailed, and versatile model. The implementation of digital twins in the offshore wind sector thus remains a challenge, as the specific needs and constraints of the domain often hinder the translation from theoretical frameworks to practical applications.

Additionally, implementing digital twins within the offshore wind and energy sectors varies significantly depending on the specific application, leading to further complexities. While the fundamental components of a digital twin should generally remain consistent, their application and the associated challenges are highly context-specific. For instance, implementing digital twins in large-scale offshore wind farms is particularly challenging due to the number of turbines and related infrastructure, extensive data collection needs from various environmental and operational sensors, and the complex optimization problems in managing these dynamic and interconnected systems. In contrast, the gap between the ideal digital twin and its practical implementation may be less pronounced in more focused applications, such as managing the lifecycle of individual turbines or optimizing maintenance schedules, where the systems involved are relatively more straightforward and more manageable (Sharma et al. 2022).

Moreover, the evaluation of digital twin performance in the energy sector is also highly domain-dependent, with different aspects prioritized depending on the operation's specific needs. In offshore wind farms, the focus might be on the digital twin’s ability to predict and mitigate potential failures or optimize energy production in response to real-time environmental conditions. In contrast, other energy applications might emphasize continuous real-time data monitoring to ensure grid stability or improve asset management. Interoperability issues add another layer of complexity, particularly when digital twins must integrate with existing systems like SCADA or ERP (Enterprise Resource Planning), which are used for operational management and logistics (Sharma et al. 2022).

Cybersecurity remains a concern, mainly as digital twins in the energy sector often operate across multiple industrial partners, utility networks, and inventory sites. The risk of data breaches and the potential leak of real-time monitoring data could have severe implications for grid security and operational integrity. Implementing digital twins also requires considerable resources, including software development costs, continuous updates, and ongoing research to keep up with advancements in IoT, big data, and ML. Integrating various components, formulating joint optimization problems, and managing large data sets can be time-consuming and may divert attention from core operational activities (Sharma et al. 2022).

Despite these challenges, some of these issues are likely to be resolved by the future evolution of the digital twin concept as a tool for predicting and optimizing the behavior of systems. There is already an expectation of advancing interconnection with AI and ML algorithms to help improve the types of predictions communicable through the framework of a digital twin (Enders and Hoßbach 2019). These advancements hold the potential to address many of the current technical and operational challenges, making digital twins more robust and capable of handling complex and dynamic environments like those in the offshore wind sector.

2.7 Conclusion to this Chapter

In summary, the literature review has highlighted the multifaceted role of digital twin technology in the offshore wind sector, mainly focusing on enhancing operational efficiency, strategic decision-making, and sustainability outcomes from an engineering point of view. The theoretical frameworks discussed, notably

Swanson and Ramiller's (1997) organizing vision framework, illustrate the importance of shared understanding among stakeholders in fostering innovation. This framework emphasizes how communities of stakeholders interpret, mobilize, and legitimize technological innovations, thus guiding the adoption of digital twin technology. Zuboff's (1988) theory of the smart machine adds depth by examining how digital twins automate operational processes while generating new insights that support organizational transformation. These technologies facilitate data-driven decision-making and real-time monitoring, which is essential for optimizing offshore wind farm operations. The collaborative nature of digital twin deployment, as explored through Nambisan et al.'s (2017) concept of distributed innovation agency, underscores the complexities of governance, interoperability, and data management that arise when multiple stakeholders are involved.

The literature also identifies gaps, particularly in exploring stakeholder engagement and organizational transformation driven by digital twins. While much of the existing research has focused on the technical aspects, the socio-technical dynamics, including the high costs, data integrity concerns, and the need for greater industry standardization, require further investigation. In conclusion, while digital twins present significant opportunities for transforming offshore wind operations, addressing adoption and integration challenges remains critical. As industries increasingly move towards digitalization, the need for more research into digital twins' practical and organizational implications is evident.

The next chapter will build on the insights gained from the literature review by outlining the methodology used in this study. It will detail the research design, data collection methods, and analytical approaches that will be employed to investigate the integration of digital twins in the offshore wind sector. This methodology aims to provide a structured approach to addressing this study's research questions and objectives, ensuring that theoretical insights and practical challenges are adequately explored.

Chapter 3: Theoretical Frameworks

3.1 Introduction

To provide a conceptual framework for this exploration, the review draws on several critical theories, including Swanson and Ramiller's (1997) Organizing Vision framework, Zuboff's (1988) theory of the smart machine, and Nambisan et al.'s (2017) distributed innovation agency and others.

3.2 Theoretical Frameworks Outlined

See Appendix A.1 for a table overview of the theoretical frameworks applied in this research. See Appendix A.2 for an outline of topics discussed in the literature review from the technological and stakeholder point of view.

3.2.1 Organizing Vision by Swanson and Ramiller

The idea of organizing vision clarifies how a group's cognitive understanding of technologies can support innovation inside and outside organizations. According to Swanson and Ramiller (1997), p. 460, an organizing vision is "a focal community idea for the application of information technology in organizations." Swanson and Ramiller (1997) assert that an inter-organizational community of diverse stakeholders formulates and implements the organizing vision. The authors contend that organizational visions emerge because they promote the growth and spread of innovation. Moreover, they argue that their assertion on organizing visions might cast buzzwords in a new light because buzzwords may indicate the emergence and growth of organizing visions. The organizing vision perspective, rooted in institutional theory, concerns how structures and procedures are adopted to support and develop the organizing vision. In this context, inter-organizational change is emphasized through institutionalization at the sectoral or societal level (Swanson and Ramiller 1997).

The organizing vision lets actors envision prospective solutions. It provides windows of opportunity since new technology could bring about many organizational options, but it only sometimes leads to innovation. To meet the challenge of implementing an IS innovation, it must also set future expectations to reduce uncertainty surrounding planning, decision-making, and action. Furthermore, according to Swanson and Ramiller (1997), the organizing vision must specify the benefits of the innovation, how it operates, the circumstances in which it may be realized, the organizational adjustments it necessitates, and the best way to apply it.

Along with other elements, including the practitioner's worldview, the business challenge, the core technology, and the adoption and dissemination process, the discourse organizes visions and acts as a developmental engine (Appendix C.1). To facilitate innovation, it specifies a list of suitable technologies. The organizational vision gives fresh significance to technology, whether new or old. The first stage of the development of IS innovation is when the organizing vision is created. According to Swanson and Ramiller (1997), prospective adopters view the organizing vision as an incomplete solution that requires additional development to meet the organization's goals. The inter-organizational community shapes the organizing vision, but the organizing vision also shapes the community since it offers fresh opportunities that draw in new players and have the potential to upend adopters' fundamental cultural presumptions. Essentially, the conversation serves as a platform for structuring the community (Giddens 1979 cited in Swanson and Ramiller (1997)).

Several circumstances may hinder the organizing vision, as noted by Swanson and Ramiller (1997). The organizing vision gets richer with time. It may yet also experience incoherence. Some may find this advantageous since it permits interpretive freedom, but it may also irritate prospective adopters and reduce the usefulness of the organizing visions for the community. Diffusion and institutionalization of the innovation later are likely to be hindered if the organizational vision remains undeveloped even after early adoption. If the basic technology functions differently than intended, it may constrain the organizing vision. The organizational vision's ultimate fate is to be forgotten by everyone, abandoned by the community, or integrated deeply into daily activities (Swanson and Ramiller 1997).

3.2.2 Zuboff's Theory of the Smart Machine

Shoshana Zuboff's (1988) theory focuses on the dual processes of automation and information, both central to understanding how digital technologies impact organizations. Automation involves replacing human labor with machine-driven processes, leading to greater efficiency. At the same time, information refers to transforming physical actions into data, allowing for new insights and decision-making capabilities. This dual process provides opportunities and challenges as organizations must balance increasing operational control through automation and empowering employees through access to more information. Zuboff's theory emphasizes how these forces shape organizational dynamics, especially the tension between centralized control and worker empowerment, prevalent in many modern digital transformations.

3.2.3 Digital Innovation and Distributed Agency

According to Nambisan et al. (2017), digital innovation is increasingly characterized by distributed agency, where innovation is not confined to a single organization but instead spans multiple actors across an ecosystem. This approach allows for collaborative development and refinement of new technologies, where various stakeholders contribute their expertise. Digital platforms, open-source systems, and cloud-based solutions facilitate this collaborative process, enabling innovation to cross organizational boundaries. Successful digital innovation requires organizations to effectively manage these complex networks of partners, ensuring proper coordination and addressing challenges such as governance and interoperability. The theory underscores the importance of ecosystem management in achieving successful digital outcomes.

3.2.4 IT Affordances and Organizational Transformation

Zammuto et al. (2007) introduced the concept of information technology (IT) affordances to explain how technology enables new organizational capabilities. Affordances refer to the potential actions that information technology makes possible within an organization, such as real-time data analysis, predictive insights, or enhanced collaboration. These affordances lead to transformations in organizational structures and processes, often breaking down silos and fostering more data-driven, process-oriented operations. However, adopting IT also introduces new challenges, such as maintaining data integrity, building trust in technology, and managing interdependencies between different systems and departments. The theory provides a framework for understanding how IT reshapes organizations while creating new complexities.

3.2.5 Functional Simplification and Closure

Kallinikos' (2005) functional simplification and closure theory examines how technology simplifies complex organizational processes by standardizing them and making them more predictable. This simplification allows organizations to manage and control their operations better. However, the theory also points out that while technology can simplify specific processes, it often introduces new complexities, especially when different systems or platforms must be integrated. The dual nature of simplification and complexity is a crucial theme in understanding the role of technology in organizational processes. It underscores the importance of managing the interdependencies that arise from technological integration, which can complicate decision-making and operational management.

3.2.6 Paradoxes of Control and Change

Tilson, Sørensen, and Lyytinen's (2021) theory on paradoxes of control and change highlights the tension between an organization's need for control over its operations and the flexibility required to adapt to change. Digital technologies often provide organizations with enhanced power through real-time data monitoring and predictive capabilities. However, these same technologies also require organizations to become more flexible in responding to the dynamic environments and shifting conditions accompanying technological adoption. The theory underscores the common challenges organizations face when balancing stability and control with the need to remain agile and adaptable to change, particularly when implementing new digital solutions.

3.2.7 Duality of Stability and Change

Farjoun's (2010) concept of the duality of stability and change argues that these two forces are interdependent rather than oppositional. Stability provides a foundation for continuous operations, while change allows organizations to innovate and adapt to new conditions. This duality is crucial for organizations that seek to remain competitive in dynamic environments. Technologies can support stability by optimizing routine operations and change by enabling new strategies and innovations. The theory suggests that organizations should not view stability and change as contradictory but as complementary forces that foster long-term success and innovation.

Chapter 4: Methodology

4.1 Introduction

To investigate the integration of digital twin technologies into the offshore wind sector, emphasizing organizational-level implications, stakeholder engagement, and perception of value, the literature review provides a few frameworks for the following analysis and debate. Among few, the organizing vision concept proposed by Swanson and Ramiller (1997) provides a theoretical foundation for this study.

4.2 Theoretical Framework of Organizing Vision

The organizing vision approach addresses interpretation, mobilization, and legitimation processes that give innovations their identity and the recognition and permission that an inter-organizational community may occasionally grant. Since the offshore wind industry comprises a network of parties with tangible and intangible interests, this research characterized it as an organizational field. Community members' attempts to see an invention as an organizational opportunity within this network have resulted in an organizing vision (Currie 2004, Swanson and Ramiller 1997).

Looking more closely at the generative environment where the organizing vision is generated is vital to comprehend how it is created. Several institutional influences shape the organizing vision via rhetorical and interpretative construction. The layers in Appendix C1, which depict the generative environment, represent the actual organizational field. Invention, adaptation, trade, adoption, application, artifacts, and practices are all included in the practical actions and items layer. The network of relationships between interested parties makes up the social structure or community layer. The structuring vision and its constitutive discourse make up the interpretive-discursive layer. The cultural-linguistic components employed to construct the discourse comprise the uppermost layer (Swanson and Ramiller 1997: 462).

4.2.1 Interpretation

An organizing vision must emerge to give the appropriate interpretation and institutional coherence, as emerging innovations are only sometimes understood, and their prospective applications may need to be more evident to potential users. Otherwise, potential adopters might need help recognizing the prospects presented by the invention and may consider it unimportant. During this procedure, the diverse group creates a shared social narrative, public theory, or account that clarifies the innovation's purpose and existence within a larger social, technological, and economic framework (Swanson and Ramiller 1997).

4.2.2 Mobilization

The organizational vision helps galvanize forces in the market that facilitate the material implementation of innovation. The idea achieves traction in the market by igniting, inspiring, and organizing entrepreneurial forces. A plethora of industry events, white papers, and technology media coverage of the breakthrough may indicate this process. In this phase, collaboration between firms can also be advantageous since it can make the innovation more conventional. Organizations can also increase their political and financial voice by forming interest groups to influence the organizing vision (Swanson and Ramiller 1997).

4.2.3 Legitimation

As part of the organizational vision, legitimacy is the process by which "the underlying rationale for information systems innovation is developed, tested, refined, and propagated." Here, prospective adopters consider the opportunities and possibilities of embracing the innovation after observing how others—often industry-leading organizations—adopt it. Essentially, the legitimacy process is reinforced by the standing and power of people who accept and promote the invention. Legitimation is frequently based on more general business issues that the public finds attractive (Currie 2004, Swanson and Ramiller 1997).

4.3 Research Framework

4.3.1 Research Design

The research project will follow the "research onion" framework outlined by Saunders et al. (2019), as seen in Appendix C.2. This model breaks down research into six layers, helping to organize and streamline the process. The research onion describes the essential layers or steps that must be completed to develop an efficient technique. Determining the primary philosophy, selecting methodologies, methods, and strategies, as well as setting time horizons are the research methodology's first steps. Together, These steps carry the research logic to the study design, which includes the primary procedures and data collection and analysis techniques (Melnikovas 2018). In the upcoming sections, the paper will dig into each layer of the research onion to help navigate this research.

4.3.2 Research Philosophy

The research is guided by interpretivism, which holds that reality is not a fixed entity but is somewhat shaped by individual experiences and perspectives (Saunders, Philip, and Thornhill 2019). In the context of this study, interpretivism provides a valuable lens for exploring the subjective meanings and perceptions that stakeholders attach to digital twin technologies within the offshore wind sector. This philosophy acknowledges that each participant's understanding is unique and influenced by their personal, organizational, and cultural backgrounds. By embracing interpretivism, this research aims to delve beyond surface-level observations to uncover how digital twins are perceived, valued, and integrated into organizational processes.

Interpretivism also supports the idea that knowledge is co-constructed between the researcher and participants (Saunders, Philip, and Thornhill 2019). In this study, semi-structured interviews allow for rich, in-depth insights as stakeholders express their views on the adoption and utility of digital twin technologies. This approach highlights the diverse and sometimes conflicting perspectives, enabling a deeper understanding of the challenges, expectations, and opportunities that digital twins represent for different stakeholders. Saunders et al. (2019) describe interpretivism as particularly suited to studies where human experience, meaning-making, and context-specific insights are central, as in this research.

4.3.3 Approaches to Theory Development (Research Type)

While interpretivism frames the philosophical foundation, this study employs a deductive approach to systematically organize and guide the research process. Starting with the Organizing Vision framework proposed by Swanson and Ramiller (1997), the study draws on established theories about adopting and diffusion technological innovations within organizational fields. The framework offers a structured means of analyzing the integration of digital twins by breaking down the process into interpretation, mobilization, and legitimation. This allows for a focused exploration of how digital twin technologies impact organizational structures, stakeholder engagement, and the perceived value within the offshore wind industry.

A deductive approach is advantageous because it provides a clear roadmap for hypothesis testing and theory validation (Saunders, Philip, and Thornhill 2019). By grounding the study in the Organizing Vision framework, the research can systematically examine whether and how existing theories align with stakeholders' real-world experiences and interpretations. This approach enables the generation of generalizable and reliable insights, enhancing the credibility and rigor of the study. Saunders et al. (2019) highlight that deductive research typically seeks to confirm or refute pre-existing hypotheses. However, it can also reveal unexpected insights when applied within an interpretive context, as theories are tested against participants' lived experiences.

4.3.4 Methodological Choice and Research Strategy

The third and fourth layers of the Research Onion outline methodological choice and research strategy, providing a comprehensive plan for achieving the study's objectives (Saunders, Philip, and Thornhill 2019). This research adopts a mono-method qualitative design using semi-structured interviews as the sole data collection technique. The decision to use a mono-method approach stems from the need to gain in-depth insights within the scope and time constraints of the study, making qualitative data best suited for this purpose.

Aligned with the interpretivism philosophy, this study employs a semi-structured interview-based research strategy to explore the complexities of digital twin adoption in the offshore wind sector (Saunders, Philip, and Thornhill 2019). This strategy provides the flexibility to delve into participants' perceptions and experiences while maintaining enough structure to ensure interview consistency. The interviews focus on understanding organizational-level implications, stakeholder engagement, and perceptions of value related to digital twin technology.

This combined approach emphasizes flexibility and adaptability - crucial components for capturing the diverse viewpoints of stakeholders across various roles within the industry. By structuring the interviews with open-ended questions, the strategy fosters an organic flow, allowing for deeper exploration of themes as they arise. This design supports both the interpretivism philosophy, which prioritizes subjective experiences, and the deductive nature of the study, enabling the analysis to align with pre-existing theories and frameworks on digital twin technology and its organizational impact.

Furthermore, a reflexive thematic analysis approach will be utilized to interpret the data collected from the interviews, following the six steps outlined by Braun and Clarke (2022). This includes familiarizing with the data, generating initial codes, identifying themes, reviewing themes, defining, and naming themes, and producing a comprehensive report. The reflexive thematic analysis allows for a structured yet interpretative exploration of the qualitative data, providing a robust framework for uncovering meaningful patterns and insights that reflect stakeholders' perspectives on digital twins.

4.3.5 Time Horizon

This study adopts a cross-sectional research design, aligning with the fifth dimension of the Research Onion. The cross-sectional approach captures insights at a single point, focusing on stakeholders' current perceptions and experiences regarding the integration of DT technology. Specifically, the data collection took place from August 22, 2024, to September 6, 2024, allowing for a focused snapshot of stakeholders' views during this period.

The chosen time horizon is ideal for this research because it emphasizes capturing stakeholders' immediate and varied perspectives on DT adoption. By conducting interviews within a defined timeframe, the study aims to explore a broad range of opinions and insights without tracking changes over an extended period. This cross-sectional approach is particularly suited to the study's objectives, as it highlights stakeholders' present attitudes and concerns, offering a foundation for understanding the challenges and potential benefits of DT technology in offshore wind operations.

4.3.6 Techniques and Procedures

4.3.6.1 Setting

This study's setting is the offshore wind industry, a sector characterized by complex and dynamic operations increasingly leveraging cutting-edge technologies such as DTs. The study explores stakeholder perceptions of digital twins' value and impact within this context. A purposive sampling strategy was employed to ensure a comprehensive understanding of the diverse perspectives on digital twin adoption. Specifically, all stakeholders who could potentially receive value from integrating digital twins into offshore wind turbines were selected for interviews.

Participants were carefully chosen from various roles within the offshore wind ecosystem, including strategic advisors, engineers, and managers. This selection ensured that the sample captured multiple experiences and expectations related to digital twin technologies across different organizational levels. Fifteen participants were involved in the study, representing internal and external stakeholders of offshore wind projects. Their roles spanned strategic advisory, operational, and technical responsibilities, providing a broad insight into how digital twins are perceived from different perspectives. Each participant had direct or indirect involvement in digital twin technology, making their feedback critical to understanding the adoption process and the perceived value of DTs within this sector.

4.3.6.2 Data Collection Method

Data for this study was collected through semi-structured interviews with 15 stakeholders from the offshore wind industry. The participants were selected based on their roles and experience with digital twin technology within their organizations. The interviews were conducted from August 22, 2024, to September 6, 2024.

All interviews were conducted via Microsoft Teams, providing a convenient and secure platform for engaging with internal and external stakeholders. The sessions varied in duration, ranging from 26 to 59 minutes, allowing each participant to share their perspectives in detail. The participants received an email invitation with a file containing the prepared set of questions, which can be seen in Appendix D. The interviews were audio-recorded with the consent of the participants (Appendix K), ensuring accurate transcription and data analysis. Each participant was asked whether they consented to the interview to be transcribed, used for this thesis, and later deleted after receiving a final grade.

For example, the interviewees held positions such as strategic Advisor Consultant, Expert Advisor, or Software Engineer. The table below shows further details about each interviewee and the recorded interview duration.

Date	Nr.	Position	Stakeholder	Method	Duration
22/08/2024	Participant 1	Strategic Advisor Consultant	Internal	Teams	40m 41s
22/08/2024	Participant 2	Expert Advisor	Internal	Teams	59m 01s
22/08/2024	Participant 3	Software Engineer	Internal	Teams	34m 29s
23/08/2024	Participant 4	Platform Director	Internal	Teams	43m 27s
23/08/2024	Participant 5	Product Director	Internal	Teams	43m 52s
27/08/2024	Participant 6	Head of Foundations	Internal	Teams	41m 47s
27/08/2024	Participant 7	Head of Digital Innovation	External	Teams	54m 09s
29/08/2024	Participant 8	Solution Architect	Internal	Teams	37m 44s
02/09/2024	Participant 9	Head of Operational Excellence	Internal	Teams	31m 21s
04/09/2024	Participant 10	Head of WTG Engineering	Internal	Teams	30m 47s
05/09/2024	Participant 11	Manager of Data Analytics	Internal	Teams	28m 46s
05/09/2024	Participant 12	Asset Manager	Internal	Teams	26m 45s
06/09/2024	Participant 13	Business Controller	Internal	Teams	36m 11s
06/09/2024	Participant 14	Data Delivery & Software Dev	Internal	Teams	55m 17s
06/09/2024	Participant 15	Principal Engineer in WTG	Internal	Teams	28m 50s

Table 6 Interviewed Participants (own work)

4.3.6.3 Data Analysis Technique

The title of this study is "Integrating Digital Twins into Offshore Wind Turbines: A Systems and Stakeholder Perspective." A reflexive thematic analysis approach was chosen for analyzing the data, as it allows for a well-rounded interpretation of participants' views, focusing on how stakeholders perceive and experience the adoption of digital twin technologies in their roles (Braun and Clarke 2022). The key objectives of this analysis were derived from the research questions and aimed at understanding the following:

1. To determine stakeholder perceptions regarding the value and needs of digital twins in the offshore wind industry.
2. To explore the expectations, roles, and needs of key stakeholders in deploying and using digital twin technology.
3. To assess the challenges faced by stakeholders in adopting digital twin technology in offshore wind projects.
4. To investigate how digital twin technologies act as catalysts for organizational transformation, focusing on changes during various stages of offshore wind projects.

To accomplish the research objectives, a reflexive thematic analysis approach was employed to analyze the qualitative data obtained from interviews with 15 stakeholders in the offshore wind industry. Braun and Clarke (2022) describe reflexive thematic analysis as a theoretically flexible and accessible approach that aids in identifying and analyzing patterns within qualitative data. This method was chosen for its ability to offer deep insights into complex organizational contexts, such as those involving the adoption of digital twin technology.

Nvivo 14, a qualitative tool that helped organize and code the data systematically, supported the data analysis. The analysis followed six key steps: familiarizing with the data, coding, generating themes, reviewing potential themes, naming them, and finally, producing the report to ensure alignment with the research objectives.

Following the first step of reflexive thematic analysis, the researcher familiarized with the data by transcribing the interview transcripts (Appendix K). After completing the transcription process, the researcher took time to read through the interview transcripts to get a general understanding of the information provided by the interviewees (Appendix K).

After familiarizing with the data, the researcher proceeded to the second step of reflexive thematic analysis, which is generating initial codes (Appendix G.1). After the initial codes had been generated, the researcher took time to review the codes and explore any emerging patterns and relationships in the codes. Related codes were subsequently grouped to generate initial themes, which represented the third step of the reflexive thematic analysis process (Appendix G.2). The fourth step of reflexive thematic analysis included reviewing the initial themes and revising the themes in a way that they answered the research questions related to the study. The fifth step of the reflexive thematic analysis process included coming up with the final names of every theme in a way that related to the research questions and the research objectives. The final themes that emerged in the research are shown in Appendix G.2.

The sixth and final stage of the reflexive thematic analysis process involved producing the report. The report represented the different codes and how they came together to form themes that answered the research questions posed in the study (Appendix H). The report also included excerpts representing the statements of different interviewed participants as evidence of various codes and themes. Furthermore, Appendix J shows the final codes and themes grouped.

4.4 Limitations

This study provides valuable insights into the perceptions of digital twin technologies within the offshore wind sector, but several limitations should be acknowledged. First, the research employed a purposive sampling approach, ensuring that relevant stakeholders with knowledge of digital twins were interviewed. However, the sample was heavily skewed, as 14 out of 15 participants came from a single company. This limits the generalizability of the findings to a broader industry context, and the conclusions may primarily reflect the company's perspectives and organizational culture.

Second, the study's cross-sectional design captured data at a single point between August 22, 2024, and September 6, 2024. While this snapshot provides insights into stakeholder perceptions, it does not account for how these perceptions or organizational practices may evolve as digital twin adoption progresses. A longitudinal study would be better suited for tracking such changes and understanding their long-term effects.

Finally, the use of semi-structured interviews and the interpretive approach introduce a degree of subjectivity. While a rigorous thematic analysis was employed, the researcher's interpretations and the participants' viewpoints still shape the findings. The reliance on self-reported data may also lead to a lack of quantitative aspects of digital twin adoption, such as technical performance metrics. Future research could benefit from a mixed-methods approach, combining qualitative insights with quantitative data for a more comprehensive understanding.

4.5 Conclusion to This Chapter

Because there are no in-depth, suitable overviews of the literature on digital twins in offshore wind, my work included summarizing the authors' work, as seen in Tables 1, 4, and 5. One critical contribution of this research is synthesizing the literature on the Stages and Applications of Digital Twins in Offshore Wind (Table 1), Stakeholders of Digital Twins (Table 4), and finally, the Value of Digital Twins to Stakeholders (Table 5).

This methodology chapter has detailed the research design, philosophical underpinnings, data collection methods, and analytical procedures employed to explore integrating digital twin technologies within the offshore wind sector. The use of a deductive, interpretivism approach, supported by the Organizing Vision framework, offers a structured yet flexible path to understanding how stakeholders perceive and interact with digital twins. Through purposive sampling and a mono-method qualitative approach, the study gathers nuanced insights from participants who are directly involved with or knowledgeable about digital twin technology.

By adopting a cross-sectional time horizon, the study captures a snapshot of stakeholder perspectives during a defined period, providing a foundation for understanding the current landscape of digital twin adoption. However, the limitations identified, including sampling constraints, time sensitivity, potential interpretive bias, and the exclusive use of qualitative data, underscore areas for future research.

The following chapter, "Results," delves into the findings from the interviews' thematic analysis. It presents and analyzes the data, offering detailed insights into how digital twin technologies are perceived within the offshore wind industry, including their perceived benefits, challenges, and transformative potential.

Chapter 5: Results

5.1 Introduction

This chapter presents the results of interviews conducted with 15 stakeholders in the offshore wind industry, focusing on their perceptions and experiences with digital twin technology. These results address the study's aim of exploring how digital twins impact organizational processes, stakeholder engagement, and value creation. The data is organized around the study's research questions, focusing on how stakeholders perceive digital twins' value, challenges, and transformative potential in offshore wind projects.

Of the fifteen participants recruited in this study, thirteen were male, and two were female (Appendix E.1). Furthermore, each participant could be classified as an Internal or External employee of the company for which the interviews were conducted. In total, 14 participants were internal, and only one was external (Appendix E.2). Finally, participants were further classified based on their business units, with as many as nine working in Project Delivery and engineering, 2 in Operational Readiness, and a single participant for each of the following business units: Offshore Development, Organizational Development, Commercial & Asset Management and Controlling Offshore (Appendix E.3). See Appendix E for all the charts related to the description of the participants.

5.2 Identified Themes

The main themes that emerged after conducting the reflexive thematic analysis included stakeholder perceptions of value creation from digital twins, stakeholder roles, expectations, and needs, challenges in adopting digital twin technology, organizational transformation, and the impact of digital twins, and finally, others. The "Others" theme contained codes referring to digital solutions, financial solutions, industry and culture solutions, technical solutions, outlook, each participant's definition of digital twins, and whether digital twins are part of their work directly or indirectly. This theme comparison can be seen in detail in Appendix H. Additionally, direct quotes from interviews are taken and labeled as follows:

- Samuel – S
- Participant 1 – P1
- Participant 2 – P2
- And so on… until P15

Furthermore, this section contains references to the Appendix for this research. To clarify, there were 15 files (participants), and each theme or category could have as many references as the researcher identified.

For example, Appendix H shows the number of files (participants who mentioned this theme) and the number of references for each theme.

5.2.1 Stakeholder Perceptions of Value Creation from Digital Twins

The theme "Stakeholder Perceptions of Value Creation from Digital Twins" emerged as the study's central focus, highlighting how participants perceive the impact of digital twin technology on various aspects of offshore wind operations. Operational Efficiency (29 references) and Long-term Strategic Value (25 references) were the most prominently referenced, indicating their critical importance to stakeholders. This theme can be seen as a concept in Appendix H.2 and a finalized decomposition tree in I.1.

In contrast, while acknowledged as necessary, Environmental and Sustainability Impact (13 references) and Risk and safety Mitigation (15 references) received relatively fewer references than long-term strategic value and operational efficiency. Although stakeholders generally agreed that digital twins could contribute positively to sustainability goals and risk management, these areas were viewed as something other than immediate priorities for value creation. Instead, the primary focus for most participants remained on the operational and financial benefits of adopting digital twins in the offshore wind sector.

Starting with Cost Savings, the distinction between Minimal and Significant cost savings was evident in the responses. Most stakeholders (9 files, fourteen references) emphasized the significant cost savings potential of digital twins, mainly through improvements in predictive maintenance, resource optimization, and the reduction of operational inefficiencies. These stakeholders viewed digital twins as a long-term investment that would yield substantial financial benefits, especially once fully integrated into offshore wind operations. On the other hand, a smaller group (3 files, four references) perceived minimal cost savings from the technology. This minority expressed concerns regarding the high initial costs of implementation and the time it might take to see a return on investment, thus questioning the short-term financial viability of digital twins.

In the subcategory of Environmental and Sustainability Impact, the contrast between High Perceived Benefit (7 files, twelve references) and Low Perceived Benefit (1 file, one reference) highlights the general optimism surrounding the environmental advantages of digital twins. Most stakeholders believed that digital twins could play a central role in advancing sustainability goals by reducing energy waste, enhancing operational efficiency, and supporting the long-term environmental strategies of offshore wind projects. However, one stakeholder expressed a low perceived benefit, potentially indicating skepticism about whether the environmental impacts of digital twins are substantial enough to justify the investment, particularly in the context of other available technologies.

Regarding long-term strategic value, stakeholders have agreed mainly on the sustainable benefits of digital twins (10 files, twenty references). They viewed the technology as a crucial element in future-proofing offshore wind operations by enabling continuous optimization and improving decision-making over the asset lifecycle. However, a smaller subset of stakeholders (5 files, five references) expressed concerns about the unsustainable aspects of digital twins, particularly when considering factors such as the fast pace of technological change, which could render current investments obsolete or insufficient in addressing future industry demands.

For Operational Efficiency, there was a near-consensus on the high impact of digital twins (13 files, twenty-eight references). Stakeholders emphasized the role of technology in significantly enhancing the efficiency of offshore wind projects by providing real-time data, improving predictive capabilities, and reducing operational errors. Only one participant raised concerns about the low impact of digital twins, perhaps suggesting that, in certain contexts or with specific implementation challenges, the efficiency gains may be less pronounced or immediately realized.

Finally, the Risk & Safety Mitigation subcategory revealed that most stakeholders felt in control (6 files, twelve references) by adopting digital twins, emphasizing how the technology could help mitigate risks and enhance safety protocols by providing accurate, real-time data. However, a few participants (3 files, three references) felt they needed to be in control, possibly reflecting concerns about the reliability of data or the complexity of integrating digital twins into existing risk management frameworks.

5.2.2 Stakeholder Roles, Expectations, and Needs

The theme "Stakeholder Roles, Expectations, and Needs" was vital in understanding how stakeholders perceive their involvement and the technological expectations associated with digital twin implementation. This theme primarily revolved around enhancing communication and collaboration and clarifying stakeholder roles in digital twin adoption, with additional attention to technological expectations and needs. It can be seen as a concept in Appendix H.3 and the finalized decomposition tree in I.2.

Expectations of Technology received the most attention, with 12 files and 25 references discussing stakeholder expectations for digital twins. Many stakeholders (11 files, nineteen references) had high expectations of the technology, emphasizing its potential to revolutionize operations through real-time data analytics and enhanced decision-making capabilities. These participants viewed digital twins as essential for driving efficiency and innovation in offshore wind operations. However, a smaller group (4 files, six references) expressed low expectations, highlighting concerns about the current limitations of the technology, such as integration challenges and data security concerns, which they felt hindered the full realization of digital twins' potential.

The Communication and Collaboration Enhancement subcategory was referenced in nine files for eleven references. Most stakeholders (six files, seven references) noted improvements in collaboration due to implementing digital twin technology. They cited better data sharing and increased transparency in decision-making processes as critical benefits. However, some stakeholders (four files, four references) reported that communication remained unchanged, suggesting that the technology had yet to impact internal collaboration and coordination fully.

Role Clarity was another significant subcategory in 9 files with 19 references. Most participants (8 files, fifteen references) felt that digital twin technology helped clarify stakeholder roles, ensuring that decision-making processes were more streamlined and better-defined responsibilities. However, a smaller group (3 files, four references) noted conflicts of roles among stakeholders, where overlapping responsibilities or a lack of clarity led to friction and inefficiencies in project management.

Lastly, the subcategory of Technological Needs was discussed in 8 files with 15 references. A substantial number of participants (7 files, ten references) indicated that their technological needs, specifically scalability, interoperability, and cybersecurity, needed to be met. These stakeholders felt that digital twin technology still needed to fully address offshore wind operations' complex demands. Conversely, a smaller group (5 files, five references) believed their needs were well-met, acknowledging that digital twins fulfilled many of their expectations, particularly in improving operational efficiency and data-driven decision-making.

5.2.3 Challenges in Adopting Digital Twins

The theme "Challenges in Adopting Digital Twins" explores the barriers stakeholders identified when integrating digital twin technology into offshore wind projects. These challenges are grouped into key areas, including the cost of implementation, interoperability issues, technical complexity, concerns about data security, and regulatory barriers. This theme can be seen as a concept in Appendix H.4 and the finalized decomposition tree in I.3.

Ten files with 18 references highlighted the cost of implementation. Most stakeholders (9 files, seventeen references) cited the high cost of implementing digital twins as a significant barrier. The initial investment required for the technology, ongoing maintenance, and operational costs made stakeholders question the short-term return on investment. Only one participant expressed a view of low cost (1 file, one reference), possibly referring to a specific context or implementation scenario where the expenses were considered manageable.

Interoperability Issues were frequently mentioned, with seven files and 20 references identifying this as a significant challenge in adopting digital twins. The majority (6 files, thirteen references) pointed to significant interoperability issues, noting the difficulty of integrating digital twin systems with existing operational infrastructure and legacy systems. These stakeholders emphasized the need for standardized protocols to ensure seamless data exchange across platforms. In contrast, a few participants (3 files, seven references) downplayed the severity of these issues, describing the interoperability concerns as insignificant or manageable with current technological capabilities.

Technical Complexity was another prominent challenge, with 11 files and 30 references. Almost all stakeholders (11 files, twenty-seven references) noted the high complexity of digital twin technology, emphasizing the steep learning curve and the need for specialized skills to manage and maintain the systems. This complexity extended to the difficulties of accurately modeling real-world conditions and ensuring the reliability of data produced by digital twins. A small minority (2 files, three references) described the low complexity of the technology in specific cases, perhaps due to more straightforward implementations or systems tailored to their operational needs.

Another challenge was Data Security and Privacy Concerns, which appeared in 5 files with nine references. All participants discussing this issue expressed high concerns (5 files, nine references), particularly around the risks associated with data breaches, cybersecurity, and the safe handling of sensitive operational information. While no participants rated this concern as low, it was clear that data security remains a critical issue that needs to be addressed for digital twins to be fully trusted by stakeholders.

Regulatory and Compliance Barriers were also mentioned, albeit less frequently, with 9 files and 12 references. Stakeholders were divided on the severity of these barriers, with some (6 files, nine references) describing them as minimal and not a significant hindrance to digital twin adoption. However, a smaller group (3 files, three references) pointed to significant regulatory hurdles, particularly around the need for compliance with evolving industry standards and regulations, which they felt could slow down implementation.

Finally, Stakeholder Resistance to Change emerged as a notable barrier in 5 files with 12 references. Most participants (5 files, eleven references) indicated strong resistance, particularly from employees and departments accustomed to traditional processes. This resistance was seen as a cultural and organizational challenge that must be managed carefully to ensure the successful adoption of digital twins. Only one participant (1 file, one reference) indicated weak resistance, implying a smoother transition to new technologies in their context.

5.2.4 Organizational Transformation and Impact of Digital Twins

The theme "Organizational Transformation and Impact of Digital Twins" investigates how integrating DTs influences various aspects of organizational processes, collaboration, and decision-making within the offshore wind sector. Stakeholders reflected on how digital twins drive cross-functional collaboration, cultural change, and overall efficiency throughout the project lifecycle. This theme can be seen as a concept in Appendix H.5 and the finalized decomposition tree in I.4.

The subcategory of Cross-functional Collaboration was mentioned in 8 files with 11 references. Stakeholders were divided in their perceptions of the technology's impact on collaboration. The majority (5 files, seven references) noted that digital twin technology had enhanced collaboration, enabling departments to share data more effectively and work together more seamlessly. However, some (4 files, four references) reported that collaboration remained static, with no noticeable improvement in cross-departmental interactions despite the implementation of digital twins.

Cultural Change was a key focus area, with 7 files and 18 references discussing the organizational shifts that digital twins can trigger. Many stakeholders (5 files, ten references) described the resistance to change within their organizations, noting that traditional mindsets and established processes hindered the adoption of digital twin technology. On the other hand, a smaller group (4 files, eight references) pointed to transformative effects, where digital twins had catalyzed a shift in organizational culture towards more data-driven and innovative approaches, helping the organization align with the future of offshore wind operations.

Eight files discussed efficiency in Project Lifecycle Management with 18 references. Stakeholders equally emphasized improvements in specific lifecycle phases (5 files, nine references) and throughout the project lifecycle (5 files, nine references). They highlighted that DTs had enhanced planning, execution, and monitoring processes, leading to greater operational efficiency. However, the focus varied between seeing benefits in isolated project stages versus realizing comprehensive, lifecycle-wide advantages.

Seven files with 12 references referenced the subcategory of Organizational Process Changes. Many stakeholders (five files, eight references) reported that digital twin technology had substantially changed organizational processes, improving workflow efficiency and decision-making accuracy. Conversely, a smaller group (four files, four references) noted only marginal changes, indicating that while digital twin technology had some positive effects, it had yet to transform the way processes were conducted in their organizations radically.

Another critical aspect was real-time decision-making, discussed in seven files with 18 references. Most stakeholders (seven files, twelve references) believed digital twins improved real-time decision-making by providing actionable insights and facilitating more informed decisions. However, a smaller subset (two files, six references) felt that the technology had kept their decision-making processes the same, perhaps due to challenges in fully integrating the technology or operationalizing the real-time data provided.

Finally, Standardization Across the Industry emerged as an important theme, with 14 files and 32 references. Stakeholders agreed on the need for greater standardization to fully realize digital twins' benefits. Most participants (13 files, twenty-six references) supported knowledge sharing across the industry, emphasizing that broader collaboration and standardization efforts would help unlock the full potential of the technology. However, some stakeholders (5 files, six references) felt that organizations were still inclined to retain knowledge, maintaining competitive advantages by limiting the dissemination of best practices and insights from their digital twin implementations.

5.2.5 Others

The final theme, "Others," represents additional findings that emerged during the analysis but were not directly related to the core research questions. These extra insights provide a broader context for adopting digital twins in offshore wind projects and reflect various perspectives on technical solutions, financial considerations, and the industry's outlook. This theme can be seen as a concept in Appendix H.6 and the finalized decomposition tree in I.5.

The subcategory Introduction was mentioned in 15 files with 30 references. Stakeholders reflected on their definition of digital twins and how they had come to understand and work with the technology. In Digital Solutions, which appeared in 8 files with 15 references, stakeholders discussed the various digital tools that support the implementation of digital twins. Cloud platforms (6 files, eight references) were frequently cited as essential for enabling the scalability and accessibility of digital twin systems. Some participants also mentioned using virtual worlds (3 files, four references) to simulate operational environments, enhancing their ability to test and refine strategies. Dashboard visualization (2 files, three references) was referenced as a crucial interface for monitoring and managing digital twin data in real time.

Financial Solutions was referenced in 11 files with 48 mentions and highlighted some key financial drivers and constraints in adopting digital twins. Business case improvement (8 files, thirteen references) was a significant focus, with stakeholders discussing how DTs could enhance operational efficiency, improve decision-making, and reduce costs over the lifecycle of a project. A notable number of stakeholders (7 files, twenty-two references) emphasized the role of digital twins in enabling lifetime extension for offshore wind assets by optimizing maintenance and performance monitoring. On the downside, two stakeholders (2 files and two references) expressed a negative financial outlook, highlighting concerns about the upfront investment and uncertainty around long-term returns.

Eight files with 16 references discussed the future outlook of digital twins. Most participants (eight files, fourteen references) expressed a positive outlook, emphasizing the growing importance of digital twins in driving innovation and efficiency in offshore wind. However, a minority (two files, two references) conveyed a negative outlook, primarily due to concerns about the high costs of implementation and the complexity of integrating digital twins with existing infrastructure.

In the subcategory Industry & Culture Solutions, mentioned by ten files with 39 references, stakeholders discussed the broader cultural and industrial factors influencing the adoption of digital twins. Conservatism in the offshore wind industry (4 files, five references) was noted as a barrier to adoption, with some organizations reluctant to embrace new technologies. Discussions about original equipment manufacturers (OEMs) (4 files, eight references) and their influence over adopting digital twins were also prevalent. Several stakeholders compared the offshore wind industry to other industries (3 files, six references), noting that sectors like manufacturing were more advanced in adopting digital twin technology. Issues around trust (4 files, five references) and uncertainty (2 files, four references) also emerged, highlighting concerns about data security and the reliability of digital twin solutions.

Finally, Technical Solutions was a significant subcategory, appearing in 14 files with 105 references. Stakeholders discussed various technical aspects of digital twin technology, focusing on integration (12 files, twenty-six references) and the challenges of ensuring that digital twins can seamlessly interact with existing operational systems. Composability (6 files, sixteen references) and design models (5 files, twenty-nine references) were also crucial topics, reflecting the technical complexity of developing and maintaining accurate digital models of real-world assets. Participants highlighted the importance of predictive maintenance (4 files, six references) as one of the digital twins' most valuable technical benefits, allowing for early detection of potential issues and minimizing downtime. Other technical challenges, such as time sensitivity (4 files, seven references) and reusability (2 files, six references), were also raised, particularly regarding how digital twin systems could adapt to changing operational conditions and be scaled across different projects.

5.2.6 Matrix Coding Query (Heatmap)

The heatmap below provides an in-depth look into how each participant engaged with the five research themes. The differences in engagement highlight how participants contributed across various aspects of digital twin adoption, which aligns with many of the key findings from the previous outputs. The sum of each of the five columns is always 100%. For instance, Participant 1 (P1) had 17,74% in column A:01, indicating that he expressed himself the most out of all participants (15) and all themes possible (5), specifically about this one.

	A: 01 Stakeholder Perceptions of Value Creation from Digital Twins RQ1	B: 02 Stakeholder Roles, Expectations, and Needs RQ2	C: 03 Challenges in Adopting Digital Twins RQ3	D: 04 Organizational Transformation and Impact of Digital Twins RQ4	E: 05 Others
1: 01. Participant	17,74%	10,88%	11,69%	6,64%	1,81%
2: 02. Participant	7,52%	5,41%	14,07%	13,52%	5,76%
3: 03. Participant	9,87%	5,47%	4,79%	10,11%	1,68%
4: 04. Participant	8,84%	12,74%	4,73%	13,96%	4,85%
5: 05. Participant	7,98%	12,06%	15,57%	2,2%	5,09%
6: 06. Participant	9,26%	7,1%	5,95%	11,57%	4,24%
7: 07. Participant	2,34%	3,27%	1,53%	0,53%	10,78%
8: 08. Participant	2,59%	10,71%	7,3%	8,87%	12,4%
9: 09. Participant	3,12%	5,24%	3,97%	6,45%	6,76%
10: 10. Participant	2,98%	5,86%	10,59%	4,65%	5,82%
11: 11. Participant	9,44%	9,08%	3,54%	6,33%	7,74%
12: 12. Participant	4,93%	7,22%	3,48%	2,73%	7,69%
13: 13. Participant	6,53%	0%	7,33%	5,02%	2,76%
14: 14. Participant	3,83%	4,11%	5,13%	6,98%	17,3%
15: 15 Participant	3,02%	0,85%	0,34%	0,43%	5,32%
Total	**100%**	**100%**	**100%**	**100%**	**100%**

Table 7 Overall Heatmap (own work)

Several participants demonstrated high engagement, starting with RQ1 (Stakeholder Perceptions of Value Creation) and RQ3 (Challenges in Adopting Digital Twins). For example, Participant 01 contributed significantly to RQ1 (17.74%) and RQ3 (11.69%), indicating a strong focus on the perceived value of digital twins and the practical challenges related to their adoption. For instance, P1 mentioned:

RQ1: On value creation

> *P1: "The ultimate dream is not just about collaboration between different software types but also between different disciplines. There's no 'mother of all digital twins'—each discipline has its domain-specific twin. For example, Google Maps is for roads, but you wouldn't use it for an oil and gas platform or an offshore wind park. The vision is a full-blown digital twin where all disciplines and systems communicate. That's the dream, though I haven't seen it fully realized yet."*

This suggests that Participant 01 may have extensively discussed operational benefits and strategic value while addressing critical issues such as technical complexity and cost. Similarly, Participant 05 had a notable presence in RQ1 (7.98%) and RQ3 (15.57%), pointing to a balanced focus between identifying value and discussing the barriers to full-scale implementation, such as the challenges of integration and technical hurdles. For example, P5 said:

RQ1: On value creation

> *P5: "The cost savings from understanding fatigue loads and optimizing designs is significant. Knowing the remaining useful life of structures is a big use case."*

RQ3: On challenges

> *P5: "You know, a lot of companies are using it in their sales materials, and internal departments are saying, "We do the digital twin for the wind farm. "As I mentioned with SSI, whereas outside, it means that the word digital twin can be diluted a bit and misunderstood in all that sales material. And the problem for someone like me, who works with it more, is that stakeholders further up in the company may believe we're doing more things than we actually are doing. Or maybe they believe when they get sales pitches from companies who say they do fancy things, believing that this will solve many of their problems—which is not true when you actually look into the true content of what the company delivers."*

In contrast, Participant 04 and Participant 11 provided a more balanced input across different themes. Participant 04 contributed notably to RQ2 (Stakeholder Roles and Expectations) (12.74%) and RQ4 (Organizational Transformation) (13.96%), indicating a comprehensive understanding of how roles and organizational dynamics evolve with digital twin implementation. Their engagement with these themes suggests they likely discussed key topics like role clarity, collaboration, and cultural changes. By way of example:

RQ4: On organizational dynamics and transformation

> *P4: "It's a bit of an old-fashioned delivery model—not just at [Company Name], but at many companies. They have a Phase 1 for product development, Phase 2 for project execution, and Phase 3 for operation. Between these, there's often poor understanding of how to take a holistic view of the whole project."*

Similarly, Participant 11 showed consistent input across RQ1 (9.44%) and RQ2 (9.08%), reflecting a dual focus on value creation aspects and stakeholders' expectations from digital twins. This balanced engagement shows that these participants were keen to explore both the benefits and challenges of adopting such technologies. Such as:

RQ2: On stakeholder expectations

> *P11: "Initially, it was a challenge to create acceptance for these digital twins and build trust with the stakeholders. But once they see the benefits, they begin to trust them."*

RQ4 (Organizational Transformation and Impact) also saw high contributions from Participant 02 (13.52%) and Participant 06 (11.57%), suggesting that these participants were focused on the broader impacts of digital twins on organizational structure and culture. Their high engagement likely involved discussions around how digital twins influence decision-making processes, collaboration, and workflow management within their organizations. For these participants, the theme of organizational transformation was of prime interest, emphasizing how digital twins can shift traditional processes and structures in offshore wind operations.

RQ1: On organizational transformation and impact

> *P02: "The idea is that this data should not only be used for lifetime extension but also for improving operations, maintenance, optimization of earnings, and so forth."* And *"Combining it with other databases and other data will also be key. The more you can combine different disciplines, the more benefit you can create and value you can get from all of this information."*

On the other hand, Participant 13 and Participant 15 had low contributions to RQ2 (0% and 0.85%, respectively), indicating minimal focus on stakeholder roles and technological expectations. This suggests that these participants were less involved in or less concerned with issues like communication and collaboration or how their roles might evolve with the implementation of digital twins. In contrast, their engagement in other themes shows that while they might not have focused heavily on roles and expectations, they could have contributed more to technical or operational discussions in other areas.

RQ4: On organizational transformation and impact

> *P13: "It's not solely a financial decision in the end. The only thing I can do is look at the benefit that the measure has, the financial impact, and then say that from a pure financial perspective, this would be the order you should execute them in."*

RQ4: On organizational transformation and impact

> *P15: "Our biggest concern is getting detailed information about the foundations because we design them ourselves, but for the turbines, we don't have detailed designs for components like blades. This limits our ability to evaluate how well the turbine is performing relative to design."* And *"Yes, we are exploring whether we need additional sensors... Last year, we did a lifetime extension for the first Danish offshore site, Horns Rev 1. We conducted a full simulation of what had happened over the past 20 years and evaluated if the turbines needed refurbishing."*

Regarding additional themes (Others), participants like Participant 08 and Participant 14 had a significant focus (12.4% and 17.3%, respectively). This aligns with earlier findings that financial and technical solutions were critical concerns for specific stakeholders. These participants likely emphasized long-term technical and financial strategies for digital twin adoption, focusing on issues like lifetime extension, business case improvements, and technical integration. Their high contributions to RQ5 suggest a more future-oriented perspective on the broader implications of digital twin technology beyond immediate operational challenges.

RQ1: On business case and future strategic value

> *P08: "The better the digital twin, the better we can make decisions on rerouting energy, capacity constraints...to increase operational stability and better support decision-making."*

5.3 Summary Tables from Interviews Outlined

See Appendix F.1, F.2, and F.3 for a table overview of each stakeholder's comparative statements on a chosen topic. There are three tables, with five participants per table and 12 rows in a single table. Each participant was asked about a topic following the logic outlined in Appendix D.2. The content of the table is derived from transcripts that can be seen in Appendix K.

5.4 Conclusion to this Chapter

The results of this study provide an understanding of stakeholder perceptions, challenges, roles, and organizational impacts surrounding the adoption of digital twin technology in the offshore wind sector. Across the four core research themes and a single extra theme, it is evident that digital twin technology is primarily viewed as a transformative tool with significant potential to drive operational efficiency, long-term strategic value, and real-time decision-making. However, stakeholders highlighted vital challenges and nuances, such as the high implementation costs, technical complexity, and the need for broader industry standardization.

In the "Stakeholder Perceptions of Value Creation" theme, stakeholders recognized the value digital twins bring regarding operational improvements and strategic positioning. However, concerns about immediate financial returns and environmental impacts were also raised. The theme "Roles, Expectations, and Needs" revealed high technological expectations and significant unmet needs, particularly around stakeholder role clarity and collaboration. Regarding "Challenges in Adopting Digital Twins," the high costs and technical barriers, especially around interoperability, emerged as primary concerns. However, stakeholders remained optimistic about the long-term potential of overcoming these challenges.

The "Organizational Transformation" theme showed that while digital twin technology influences organizational culture and processes, there is still resistance to change and inconsistency in process adaptation. Lastly, the "Others" theme captured a broader range of technical, financial, and industry-specific insights, indicating that while many stakeholders are optimistic, concerns about financial and cultural hurdles remain.

As we transition to the Discussion Chapter, we will shift to interpreting these results in greater depth. We will explore how these findings align with or challenge the existing literature, providing insight into where this study fits within the broader research landscape on digital twin technology. Furthermore, we will relate these findings to the original research questions, evaluating how the study answers those questions and uncovers new dimensions that could have been initially anticipated. The discussion will also focus on identifying the practical implications of these findings, offering insights into how the challenges can be addressed and how digital twin technology can be better integrated into the offshore wind sector. This critical reflection will help shape the conclusions and recommendations for future research and practice.

Chapter 6: Discussion

6.1 Introduction

This study explores how stakeholders perceive the value created by implementing digital twins in offshore wind. A gap remains in understanding how offshore wind farm stakeholders perceive the value of digital twins. Most existing studies focus on the technical aspects of digital twins, often overlooking the human element: how stakeholders engage with and benefit from these innovations. This research aims to understand how digital twin technology can be effectively integrated into offshore wind projects, emphasizing its impact on stakeholders and organizational transformation. The key objectives are to (1) assess stakeholder perceptions of digital twins in the offshore wind context, (2) identify the challenges related to adoption and scaling, and (3) evaluate how digital twins facilitate organizational transformation. The primary research question focuses on how different stakeholders perceive the value of digital twin technology in offshore wind projects. At the same time, sub-questions explore the roles, challenges, and transformative potential of these technologies within the industry.

A qualitative approach was employed, gathering data through semi-structured interviews with 15 key stakeholders in the offshore wind industry, including strategic advisors, engineers, and project managers. The study applied Swanson and Ramiller's (1997) Organizing Vision framework to explore how digital twin technologies are interpreted, mobilized, and legitimized within organizational contexts. Reflexive thematic analysis was used to analyze the interview data and identify key themes related to stakeholder perceptions and organizational challenges. This chapter aims to interpret and present the key findings from the data analysis about the research objectives. The chapter is divided into six sections: The first introduces the study, followed by an overview of the key findings. Next, the findings are interpreted through the Organizing Vision framework, including stakeholder perceptions, roles, and challenges in adopting digital twins. The final sections highlight organizational transformations.

6.2 Overview of Key Findings

The data suggest that stakeholders perceive digital twin technology as a transformative tool for enhancing operational efficiency and delivering long-term strategic value within the offshore wind sector. Many participants emphasized its potential for significant cost savings, primarily driven by improvements in predictive maintenance and resource optimization, echoing findings from the literature highlighting the role of digital twins in streamlining operations and reducing downtime (Jiang et al. 2021). These financial and operational benefits were considered the core drivers of digital twin adoption. In contrast, though acknowledged as important, environmental sustainability and risk mitigation were not seen as immediate priorities in the value-creation process. This aligns with the focus on financial and operational returns found in previous studies (Parmar, Leiponen, and Thomas 2020) , suggesting that while sustainability goals are part of the broader narrative, they are often secondary to financial considerations in the short term.

The findings also highlight a divide in stakeholder perceptions regarding the technological expectations of digital twins. While most participants expressed high expectations, viewing the technology as a game-changer for real-time data analytics and decision-making, a minority remained skeptical. This skepticism stemmed from concerns about high initial costs and the extended time required to realize a return on investment, an issue also noted in the literature as a barrier to widespread adoption (Olatunji et al. 2021). Furthermore, data security and system integration challenges were frequently cited, with several stakeholders expressing frustration over the complexity of integrating digital twins with existing infrastructure. These findings underscore the need for more effective communication about digital twins' capabilities and financial implications, particularly to manage stakeholder expectations and address concerns about short-term viability.

6.3 Interpretation of Findings

6.3.1 Organizing Vision Framework

Swanson and Ramiller's (1997) Organizing Vision framework is the central theoretical lens for understanding how digital twins are conceptualized and adopted within the offshore wind industry. This framework addresses how communities of stakeholders form shared interpretations and understandings about new technologies, guiding their adoption and integration into organizational processes.

6.3.1.1 Stakeholders' Interpretations and Adoption of Digital Twins

As discussed in Section 5.2.1, stakeholders view digital twins as a means of achieving operational efficiency, with real-time monitoring and predictive maintenance being critical drivers of value creation. This directly addresses the research objective of evaluating stakeholder perceptions regarding the needs and value of digital twins in offshore wind projects. Engineers and operators perceive the value of digital twins through their ability to enhance operational control and reduce downtime. This aligns with Swanson and Ramiller's (1997) view that an organizing vision must articulate the technology's technical capabilities and potential to address broader organizational objectives.

6.3.1.2 Misalignments and Challenges in the Organizing Vision

However, the organizing vision needs to be improved. As highlighted in Section 5.2.3, there needs to be more alignment between stakeholder expectations and the technological limitations of digital twins, particularly regarding data reliability and system interoperability. For example, it is crucial to determine which part of the offshore wind turbine is the digital twin intended for, as there is usual development of DT depends on the individual components. These challenges directly relate to the research question on the main challenges of adopting digital twins. This misalignment reveals gaps in the organizing vision that must be addressed to ensure successful adoption across all levels of the organization. Swanson and Ramiller (1997) argue that for an organizing vision to succeed, it must evolve alongside the technology, incorporating its potential and limitations. In this case, the organizing vision must be updated to acknowledge and address these technical challenges, ensuring stakeholders remain aligned in understanding the opportunities and constraints of digital twins.

6.3.1.3 Organizational Transformations Driven by Digital Twins

The organizing vision must also reflect the broader organizational transformations enabled by digital twins, as highlighted in Section 5.2.4. Integrating digital twins may lead to significant shifts in how work is organized within offshore wind operations, particularly in cross-functional collaboration and decentralized decision-making. Traditional organizational silos could be dismantled as digital twins allow for real-time data sharing across departments, leading to more collaborative workflows. This evolution in organizational structure must be incorporated into the organizing vision for digital twins, addressing how they serve as catalysts for organizational transformation across various project stages.

6.3.1.4 Adaptation, Agility, and Organizational Learning

Additionally, the organizing vision should consider the role of agility and adaptation in the face of operational challenges. As digital twins could become central to the management of offshore wind farms, the technology must be viewed not only as a tool for enhancing operational control but also as a catalyst for organizational learning. Swanson and Ramiller's (1997) framework suggests that an organizing vision should guide stakeholders in adapting to new challenges and opportunities. This means shaping a vision beyond operational efficiency and emphasizing continuous innovation and resilience in dynamic environments for digital twins.

6.3.2 Zuboff's Theory of the Smart Machine

Shoshana Zuboff's (1988) seminal work In the Age of the Smart Machine offers a profound theoretical foundation for understanding the transformative potential of information technology within organizations, mainly through the dual processes of automation and information. Burton-Jones (2014) revisits this work and highlights its relevance in analyzing digital systems' organizational and technological impacts. Zuboff's theory provides valuable insights for interpreting the results of this study, particularly in the context of the adoption and integration of digital twins.

6.3.2.1 Automation and Information

One of Zuboff's central contributions is the distinction between automation - the ability of technology to take over human tasks - and information, which involves technology's capacity to generate new knowledge by transforming processes into data that can be analyzed and acted upon (Burton-Jones 2014). In the context of digital twins, both concepts are relevant.

As discussed in Section 5.2.1, digital twins automate several operational processes, particularly in areas such as predictive maintenance and real-time performance monitoring. This aligns with Zuboff's idea of automation, where digital systems reduce the need for human intervention in repetitive tasks by performing them more efficiently. However, digital twins also informate by providing detailed data on turbine performance, enabling operators and decision-makers to gain new insights into operational patterns and optimize systems more effectively. This reflects Zuboff's (1988) argument that IT systems do more than automate - they also transform work by generating new knowledge that can reshape organizational strategies.

6.3.2.2 Dilemmas of Knowledge and Authority

Zuboff also emphasizes the dilemmas of knowledge and authority that arise when IT is integrated into organizational processes. In the case of digital twins, these dilemmas are particularly evident. The shift from physical engagement with turbines to data-driven management introduces new challenges for workers, as noted in Section 5.2.4. Operators who previously relied on manual oversight must now interpret complex datasets generated by digital twins. This shift reflects what Zuboff (1988) termed the "dilemma of knowledge", where workers must acquire new skills to engage with the digital representation of physical processes.

Additionally, Zuboff's dilemma of authority is relevant when examining the power dynamics introduced by digital twins. As noted in Section 5.2.3, introducing digital twins has shifted some decision-making power from managers to IT-literate employees who can leverage real-time data for operational decisions. This decentralization of authority aligns with Zuboff's theory (1988), where the shift in knowledge structures - driven by IT - alters traditional power hierarchies within organizations. Managers who may not possess the technical expertise to interpret digital twin data may feel vulnerable, as their authority is challenged by those who control the new knowledge created by the technology (Burton-Jones 2014).

6.3.2.3 Information for Control or Empowerment

Zuboff also explored the dual potential of IT systems to empower workers by expanding their knowledge or to control them by increasing surveillance and reducing autonomy (Zuboff 1988). In the context of digital twins, this dual potential is evident. While digital twins empower operators and engineers by providing them with rich data for predictive insights, they also increase surveillance over operational processes. Managers can use the constant flow of data generated by digital twins to closely monitor performance, which can lead to tensions between operational efficiency and worker autonomy, as discussed in Section 5.2.4.

Burton-Jones (2014) highlights how Zuboff's work draws attention to this tension between control and empowerment, where IT systems can simultaneously enhance capabilities while imposing new constraints. In offshore wind operations, the information potential of digital twins could lead to significant operational improvements. However, it also raises concerns about over-reliance on data and the potential for micromanagement. Organizations must navigate these tensions carefully, ensuring digital twins empower employees rather than merely enforce managerial control.

6.3.3 Digital Innovation and Distributed Agency

The concept of distributed innovation agency from Nambisan et al. (2017) provides an additional framework for interpreting how digital twins foster innovation in the offshore wind industry. Digital twins operate within a network of stakeholders, including operators, technology providers, and regulators, as discussed in Section 5.2.1. This distributed model reflects Nambisan et al.'s (2017) observation that digital innovation is increasingly decentralized, with multiple actors contributing to developing, implementing, and refining new technologies.

However, as discussed in Section 5.2.3, the complexity of integrating digital twins across various systems and platforms introduces new challenges. Nambisan et al. (2017) highlight that for distributed innovation to succeed, there must be clear protocols for collaboration and interoperability between different technologies. The findings underscore the need for more robust data governance frameworks to ensure that the innovation potential of digital twins is fully realized, addressing the challenge of adopting digital twin technology.

6.3.4 IT and the Changing Fabric of Organization

Insights from Zammuto et al. (2007) are relevant to understanding how digital twins are reshaping organizational structures. As noted in Section 5.2.1, digital twins enable real-time monitoring and predictive maintenance, streamlining operations by making data-driven decisions more efficient. This directly addresses stakeholder perceptions of the value provided by digital twins in offshore wind operations, where efficiency and cost-saving potential are primary drivers of value creation.

Additionally, Section 5.2.4 highlighted that digital twins drive collaborative decision-making and break down organizational silos. Teams that would traditionally work in isolation now collaborate across departments, reflecting Zammuto et al.'s (2007) concept of mass collaboration enabled by IT. Digital twins, therefore, serve as tools for organizational transformation, promoting more flexible, dynamic work processes that adapt to changing conditions.

However, the findings in Section 5.2.3 also reveal that the effectiveness of these IT-enabled transformations depends on the data's reliability. Zammuto et al. (2007) argue that the success of IT innovations hinges on the quality and trustworthiness of the data that underpins decision-making. If data from digital twins is compromised - due to data integrity or interoperability issues - the entire organizational structure that depends on this data becomes vulnerable. Thus, while digital twins have the potential to reshape organizations, their success relies heavily on the robustness of the data systems that support them.

6.3.5 Functional Simplification and Closure

Kallinikos' (2005) functional simplification and closure theory helps us understand how digital twins simplify the complex processes of managing offshore wind operations. As described in Section 5.2.1, digital twins reduce the complexity of operational tasks by transforming large amounts of data into actionable insights. This aligns with Kallinikos' concept of functional simplification, where technology reduces the complexity of operations by standardizing processes and making outcomes more predictable.

However, as noted in Section 5.2.3, digital twins also introduce new interdependencies that complicate the notion of functional closure. Kallinikos (2005) warns that interconnected systems, such as those involving digital twins, create new layers of complexity because they depend on integrating multiple platforms and data sources. The technical challenges associated with data interoperability and system integration can undermine functional closure's predictability. Therefore, while digital twins simplify some aspects of offshore wind management, they also create new vulnerabilities related to the complexity of interconnected systems.

Section 5.2.4 showed that workflow restructuring due to digital twins brings both efficiency and dependence on automated systems. Kallinikos' (2005) idea of functional closure suggests that while digital twins help organizations standardize processes, they also require careful management of technical dependencies to ensure that unexpected challenges can still be addressed.

6.3.6 Paradoxes of Control and Change

Tilson, Sørensen, and Lyytinen's (2021) theory on paradoxes of control and change is particularly relevant to understanding the tensions introduced by digital twins. In Section 5.2.3, the findings highlight a paradox: digital twins provide organizations with greater control over operations through real-time data, yet they also require organizations to be more flexible in responding to dynamic environmental conditions. This paradox aligns with Tilson et al.'s (2021) observation that digital technologies often create sociotechnical tensions, where the desire for stability and control must be balanced with the need for adaptability.

In Section 5.2.4, the paradox becomes even more pronounced as digital twins increase operational oversight while demanding that organizations maintain agility to respond to changes in the external environment, such as unpredictable weather or system failures. Managing this paradox requires organizations to develop resilience and adaptability, ensuring that digital twins are tools for control and flexible responses to challenges.

6.3.7 Duality of Stability and Change

Farjoun's (2010) concept of the duality of stability and change offers a critical perspective on how digital twins foster operational stability and organizational innovation. In Section 5.2.1, digital twins were shown to provide stability by enabling predictive maintenance and real-time monitoring, ensuring that operations run smoothly, and downtime is minimized. However, as noted in Section 5.2.4, digital twins also drive organizational change by encouraging more collaborative decision-making and cross-functional work processes. This reflects Farjoun's (2010) argument that stability and change are not oppositional forces but somewhat interdependent elements that reinforce one another.

The findings show that digital twins offer a stable foundation for routine operations while promoting innovation by enabling organizations to adapt to new challenges. For example, by analyzing the data generated by digital twins, organizations can identify new ways to optimize turbine performance or respond to changes in environmental conditions. This can subsequently lead to more precise estimations of lifetime extensions of the offshore wind farm or improved O&M in a sense that after analyzing the data, there is no need for a crew to board the vessel and investigate operational issues in person, rather than using sensors.

6.4 Conclusion to this Chapter

Adopting digital twins within the offshore wind sector brings substantial opportunities and significant challenges. This chapter has discussed how digital twin technology is generally perceived as a powerful tool for enhancing operational efficiency, enabling predictive maintenance, and providing long-term strategic value. Stakeholders recognize the value of real-time data and predictive analytics, which align with cost reduction and operational optimization objectives.

However, the complexities of integrating digital twins into existing organizational infrastructures reveal a more subjective picture. Interoperability issues, high initial implementation costs, and concerns about data security remain significant barriers to widespread adoption. These technical and financial challenges are further compounded by cultural and organizational resistance, particularly among stakeholders less familiar with advanced digital technologies.

Several theoretical frameworks discussed in this chapter help to contextualize these findings. Zuboff's theory (1988) of the smart machine underscores the dual nature of digital twins, where automation improves efficiency. However, it simultaneously raises concerns about the over-reliance on data and the potential for managerial micromanagement. The tension between control and empowerment is particularly relevant in this context, as organizations strive to balance operational oversight with flexibility for employees to leverage real-time data effectively.

The concept of distributed agency, as outlined by Nambisan et al. (2017), highlights the collaborative nature of digital innovation. This study shows that digital twin adoption requires coordinated efforts among various stakeholders. However, with standardized data sharing and collaboration protocols, these efforts often stay within their potential. As stakeholders become increasingly aware of the importance of data governance and technical interoperability, industry standards will evolve to support more cohesive integration of digital twins.

Organizational transformation is a central theme in this discussion. Zammuto et al.'s (2007) theory of IT affordances suggests that digital technologies like twins reshape organizational structures by promoting cross-functional collaboration and data-driven decision-making. The findings from this study align with this theory, showing that digital twins enable departments to work more cohesively, breaking down silos and fostering more dynamic workflows. Nevertheless, the effectiveness of these transformations is heavily reliant on the quality and trustworthiness of the data driving these systems.

Kallinikos' (2005) functional simplification and closure theory adds another layer of understanding, particularly regarding the paradox of simplification and complexity. While digital twins may simplify many operational processes by standardizing data and optimizing workflows, they also introduce significant complexities related to integrating multiple data platforms and systems. This duality is crucial for organizations to navigate as they seek to balance the benefits of automation with the challenges of managing interdependent systems.

Finally, the paradox of control and change, as explored by Tilson, Sørensen, and Lyytinen (2021), is evident in the adoption of digital twins. While these technologies provide greater control over operations through real-time data, they also demand flexibility to adapt to evolving external conditions. This study shows that managing this balance is a crucial challenge for organizations, particularly as they scale digital twin adoption across various components of a wind turbine or even a wind farm.

In summary, integrating digital twins in the offshore wind industry offers transformative potential by enhancing operational efficiency, enabling predictive maintenance, and improving stakeholder collaboration. However, technological integration, interoperability, and stakeholder alignment challenges indicate that adopting digital twins requires a strategic approach that balances these benefits with the associated complexities. Theoretical frameworks such as Zuboff's smart machine theory (1988), Nambisan's distributed innovation agency (2017), and Kallinikos's simplification and complexity paradox (2005) provide valuable insights into organizations' opportunities and challenges. Moving forward, it is crucial to address these challenges to fully realize the potential of digital twins in transforming offshore wind operations.

This chapter has laid the groundwork for the final chapter, where the findings will be summarized about the research questions, followed by a discussion of the study's limitations and recommendations for future research. Additionally, the final chapter will highlight the contributions of this research to both theory and practice, offering insights that apply not only to the offshore wind sector but to the broader field of digital transformation in industry.

Chapter 7: Conclusion

This chapter begins by summarizing the key findings of the research, addressing the main research question and sub-questions. The study's limitations are discussed, focusing on scope, methodology, and data constraints. Recommendations for future research are then outlined, identifying areas for further exploration and ways to overcome the limitations. Finally, the chapter highlights the contribution of this study to both practical applications in the offshore wind industry and theoretical advancements in digital transformation.

7.1 Summary of Findings

This study sought to explore how different stakeholders perceive value creation provided by implementing digital twins in offshore wind projects. The main research question guiding the study was:

How do different stakeholders perceive the value creation provided by implementing digital twins in offshore wind projects?

The analysis revealed that stakeholders primarily perceive the value of digital twins through their ability to improve operational efficiency, particularly by enhancing predictive maintenance, real-time performance monitoring, and data-driven decision-making. These operational benefits were highlighted in Section 5.2.1 as the primary drivers of value creation, especially in reducing downtime and operational costs. However, Section 5.2.3 pointed to significant challenges, such as data reliability, system interoperability, and the high costs of implementation, which temper the perceived value. Despite these limitations, the Organizing Vision framework (Swanson and Ramiller 1997) applied in Section 6.3.1 helped explain how stakeholders collectively interpret and communicate the value of digital twins. While stakeholders acknowledge the potential for value creation, they also emphasize the need for further technological improvements to unlock these benefits fully.

Sub-question 1 (SQ1): *How do stakeholders perceive the needs and value of digital twins in the context of offshore wind?*

The findings show that stakeholders view digital twins as essential for enhancing operational efficiency by providing real-time data analysis and predictive maintenance, as discussed in Section 5.2.1. Engineers highly value digital twins for optimizing equipment performance and minimizing downtime. At the same time, non-technical stakeholders, such as project managers and other employees, focus on extending the assets' lifetime and improving overall business cases. These perceptions align with the Organizing Vision (1997) framework, where stakeholders develop a shared understanding of digital twins as key to reducing operational risks and promoting long-term sustainability.

Sub-question 2 (SQ2): *What are the expectations, roles, and needs of critical stakeholders in the deployment of digital twin technology?*

Stakeholders' expectations vary depending on their roles within the offshore wind sector. For instance, project developers expect digital twins to improve project oversight and monitoring, while operators expect real-time data access to optimize turbine performance. Section 5.2.1 underscored the importance of clear role definitions and effective collaboration among stakeholder groups to deploy digital twins successfully. The distributed innovation theory (2017) discussed in Section 6.3.3 supports this, showing how multiple actors collaborate to meet the project's needs.

Sub-question 3 (SQ3): *What are the main challenges related to the adoption of digital twins in the offshore wind?*

The study identified several significant challenges to adopting digital twins, including data interoperability issues, system integration complexities, and scaling costs, as outlined in Section 5.2.3. Theories such as functional simplification, closure (Kallinikos 2005) , and IT affordances (Zammuto et al. 2007), discussed in Sections 6.3.4 and 6.3.5, provide insights into these challenges. These frameworks explain how digital twins can simplify operations while simultaneously introducing new complexities, particularly when integrating with existing infrastructure. Therefore, the research objective of assessing the challenges of adopting digital twins was successfully addressed.

Sub-question 4 (SQ4): *How do digital twins serve as catalysts for organizational transformation across the different stages of offshore wind farm projects?*

The study found that digital twins transform organizations by enabling cross-functional collaboration and decentralized decision-making, as discussed in Section 5.2.4. By providing real-time data-sharing capabilities, digital twins help break down traditional organizational silos, fostering greater collaboration across departments. The paradoxes of control and change (Tilson, Sorensen, and Lyytinen 2021) and the duality of stability and change (Farjoun 2010), explored in Sections 6.3.6 and 6.3.7, explain how digital twins balance the need for operational control with the flexibility required for innovation. Thus, the research objective of examining how digital twins drive organizational transformation was achieved.

7.2 Limitations of the Research

While this research offers valuable insights into the role of digital twins in the offshore wind sector, several broader limitations must be acknowledged, which may influence the generalizability and applicability of the findings.

One central area for improvement is the scope of the research, which needed to be more well-defined at the outset. The focus of the research was intended to explore digital twins in offshore wind, specifically within the domain of offshore foundations (monopiles), as was the focus of the partnering team, "Support Structure Integrity." However, during the interviews, participants discussed digital twin applications more broadly, covering entire wind turbine systems and even complete wind farm operations. This lack of focus may have led to more generalized conclusions that do not specifically address digital twin technology's unique challenges and potential when applied solely to foundations. As such, the findings may only partially represent the primary subject matter, potentially reducing their relevance to specific aspects of digital twin technology, such as its application to monopile structures.

Another significant limitation is the sample composition. Although the research involved 15 interviews, 14 participants were drawn from a single company (Appendix E.2). This creates a context-specific bias, meaning the conclusions are heavily informed by one company's organizational culture, priorities, and operational methods. As a result, these findings may not be applicable across the broader offshore wind industry, especially when considering other companies' different organizational structures, operational models, or technological strategies. For example, companies with different regulatory requirements, geographical locations, or levels of technological maturity may encounter different challenges or benefits when adopting digital twin technology. Future studies must incorporate a more diverse range of companies and stakeholders, including government representatives, external technology providers, and regulatory bodies, to gain a more holistic view.

The diversity of the participants also presents a limitation. While the interviewees represented a range of roles - from engineers directly involved in developing digital twins to stakeholders whose exposure to the technology was more marginal - this broad spectrum may have diluted the specificity of the findings. Digital twin technology is a simple but complicated tool that impacts various roles differently. While gathering a wide range of perspectives was essential for understanding the broader context, it may have led to less detailed insights into how digital twins are perceived and utilized by those more directly involved in their deployment and operation. Engineers and technical managers, for instance, may have different priorities compared to non-technical stakeholders like financial officers, leading to a broad but potentially shallow understanding of the technology's impact.

Another fundamental limitation is the time-bound nature of the research. The study's cross-sectional design captures stakeholder perceptions simultaneously, specifically between August 22, 2024, and September 6, 2024. This snapshot may not reflect the dynamic and evolving nature of digital twin adoption in offshore wind. As the technology matures and becomes more integrated into operational workflows, stakeholder perceptions, adoption rates, and organizational impacts will likely shift. Therefore, the study may need to account for the long-term transformative effects of digital twins or how organizations adapt and refine their use of the technology over time. A longitudinal study would better understand how digital twin adoption evolves and its long-term impacts on operational processes and stakeholder engagement.

Lastly, academic literature on digital twins in offshore wind is scarce beyond the technical aspects. While technical literature exists on specific technological components, such as how digital twins are integrated with specific wind turbine technologies (see section 2.5), there needs to be more research that explores the broader organizational, managerial, and stakeholder engagement aspects. It was challenging to frame the study's findings within a larger theoretical context, as the research field is still emerging. The limited body of literature restricts the ability to compare and validate the study's findings against broader academic work. The organizational and strategic impacts of digital twins, particularly their role in transforming operations, stakeholder relations, and decision-making processes, remain underexplored, limiting the extent to which the findings can be generalized or compared with existing studies.

7.3 Recommendations for Future Research

Building on the insights gained from this study and recognizing its limitations, several opportunities for future research emerge. Firstly, to better understand the broader implications of digital twins in offshore wind, future studies could expand the scope of the research to include a more diverse range of stakeholders. This study was primarily limited to internal stakeholders from one company, which may limit the generalizability of the findings across the wider industry. A more representative sample, including stakeholders from other companies, government agencies, and non-governmental organizations, would provide a more comprehensive understanding of how digital twins are perceived across different contexts.

Moreover, further research is needed to quantify the value of digital twins for various stakeholders. While this study explored qualitative perceptions of value, future studies could develop quantitative frameworks to measure the economic, operational, and strategic benefits digital twins bring to different actors in the offshore wind ecosystem. This approach would provide more apparent metrics and enable a more objective comparison of the technology's value to various stakeholders.

Another recommendation involves longitudinal studies that explore how stakeholder perceptions evolve as digital twins become more integrated into daily operations. This study provided a snapshot of current perceptions, but future research could examine how these perspectives shift over time as digital twin technology matures and is adopted more widely. Long-term studies could also investigate the role of digital twins in driving organizational transformation, examining how they contribute to changes in decision-making, operational efficiency, and collaboration across departments.

Finally, further research should focus on overcoming the technological challenges highlighted in this study, particularly around data interoperability and system integration. The success of digital twins largely depends on seamless data sharing between various components and stakeholders, yet this remains a significant challenge. Future studies could explore solutions to these technical barriers, such as developing standardized protocols for data exchange or creating more resilient systems that can withstand the harsh conditions of offshore environments.

7.4 Contribution

This study contributes to digital twin technology's practical and theoretical realms, particularly in the offshore wind sector. The research also fills a gap in the existing body of literature by providing a more holistic view of digital twins' role in transforming organizational processes and stakeholder engagement.

7.4.1 Practical Contribution

From a practical standpoint, the research offers tangible insights into adopting digital twin technology within the offshore wind industry. Specifically, it highlights how digital twins enhance operational efficiency by enabling predictive maintenance, real-time monitoring, and data-driven decision-making processes. The offshore wind sector organizations can use the findings to improve their deployment strategies for digital twins, optimizing turbine performance and reducing operational costs. Additionally, by understanding stakeholder needs and expectations, organizations can better tailor their adoption approaches to maximize the value created by digital twins, ensuring more strategic long-term planning and asset management.

7.4.2 Theoretical Contribution

Theoretically, this study builds on and contributes to the existing frameworks of digital transformation, notably Swanson and Ramiller's (1997) Organizing Vision framework and Zuboff's (1988) Theory of the Smart Machine. By applying these frameworks to the context of offshore wind, this research enhances our understanding of how digital twins drive organizational change. It adds depth to the theory by demonstrating how digital twins balance the duality of control and change, enabling decentralized decision-making while maintaining operational oversight. Furthermore, this study illustrates how digital twins' information generates actionable insights that reshape organizational strategies. It supports Zuboff's (1988) argument that IT systems do more than automate—they also transform decision-making processes by producing new knowledge. This work also enriches the Distributed Innovation theory (2017) by showing how multiple organizational actors collaborate on deploying digital twins, each contributing to the innovation process despite varying roles and expectations.

7.4.3 Research Contribution

From a research perspective, this study addresses a gap in the literature on digital twins in offshore wind, particularly regarding stakeholder engagement and value creation beyond the technological aspects. Most existing studies focus on the technical integration of individual components of digital twins with offshore wind turbines, leaving the organizational and managerial impacts largely unexplored. This research attempts to bridge that gap by providing empirical evidence on how digital twins affect decision-making processes, stakeholder dynamics, and organizational transformation. It also highlights the challenges associated with data interoperability and scaling, offering a critical perspective on the barriers to full-scale adoption. By investigating how different stakeholders perceive the value of digital twins, this study provides a foundation for future research on the socio-technical aspects of digital twin integration.

7.5 Conclusion to the Document

This study aimed to explore the integration of digital twin technology within the offshore wind industry, focusing on organizational impacts, stakeholder engagement, and perceived value creation. The findings reveal that digital twins offer substantial benefits, including improved predictive maintenance, enhanced real-time performance monitoring, and decision-making support, all contributing to increased operational efficiency and sustainability. However, challenges such as data reliability and system interoperability highlight the need for further technological advancements.

By addressing the research questions, the study demonstrated how stakeholders, including engineers and operators, perceive digital twins' operational and strategic value. It also outlined stakeholders' varying roles and expectations, emphasizing the importance of collaboration for successful implementation. Moreover, the findings confirmed that technology such as digital twins may catalyze organizational transformation by enabling cross-functional collaboration.

Despite these insights, the study's limitations must be acknowledged, including the sample's narrow focus and the evolving nature of digital twin technology. Recommendations for future research have been made to expand understanding beyond a single company context and quantify the value digital twins provide to different stakeholders more precisely.

Ultimately, this research contributes to both the practical and theoretical domains of digital twin technology in offshore wind projects, illustrating their potential to transform operational and strategic frameworks while advocating for more inclusive and robust technological development.

References

Allen, B.D. (n.d.) *Digital Twins and Living Models at NASA*. [online] available from <https://ntrs.nasa.gov/citations/20210023699> [21 October 2024]

Alstyne, M.W.V., Parker, G.G., and Choudary, S.P. (n.d.) *Pipelines, Platforms, and the New Rules of Strategy*.

Ambarita, E.E., Karlsen, A., Scibilia, F., and Hasan, A. (2024) 'Industrial Digital Twins in Offshore Wind Farms'. *Energy Informatics* 7 (1), 5

Augustyn, D., Ulriksen, M.D., and Sørensen, J.D. (2021) 'Reliability Updating of Offshore Wind Substructures by Use of Digital Twin Information'. *Energies* 14 (18), 5859

Baskerville, R.L., Myers, M.D., and Yoo, Y. (2020) *Digital First: The Ontological Reversal and New Challenges for IS Research*.

Batty, M. (2018) 'Digital Twins'. *Environment and Planning B: Urban Analytics and City Science* 45 (5), 817–820

BIS Research. (2020) *Statista* [online] available from <https://www-statista-com.esc-web.lib.cbs.dk/statistics/1296187/global-digital-twin-market-by-industry/> [29 July 2024]

Branlard, E., Giardina, D., and Brown, C.S.D. (2020) 'Augmented Kalman Filter with a Reduced Mechanical Model to Estimate Tower Loads on a Land-Based Wind Turbine: A Step towards Digital-Twin Simulations'. *Wind Energy Science* 5 (3), 1155–1167

Branlard, E., Jonkman, J., Brown, C., and Zhang, J. (2024) 'A Digital Twin Solution for Floating Offshore Wind Turbines Validated Using a Full-Scale Prototype'. *Wind Energy Science* 9 (1), 1–24

Branlard, E., Jonkman, J., Dana, S., and Doubrawa, P. (2020) 'A Digital Twin Based on OpenFAST Linearizations for Real-Time Load and Fatigue Estimation of Land-Based Turbines'. *Journal of Physics: Conference Series* 1618 (2), 022030

Braun, V. and Clarke, V. (Associate P. in S.S. (2022) *Thematic Analysis: A Practical Guide*. London ; SAGE

Burton-Jones, A. (2014) 'What Have We Learned from the Smart Machine?' *Information and Organization* 24 (2), 71–105

Chetan, M., Yao, S., and Griffith, D.T. (2021) 'Multi-Fidelity Digital Twin Structural Model for a Sub-Scale Downwind Wind Turbine Rotor Blade'. *Wind Energy* 24 (12), 1368–1387

Cimino, C., Negri, E., and Fumagalli, L. (2019) 'Review of Digital Twin Applications in Manufacturing'. *Computers in Industry* 113, 103130

Ciuriuc, A., Rapha, J.I., Guanche, R., and Domínguez-García, J.L. (2022) 'Digital Tools for Floating Offshore Wind Turbines (FOWT): A State of the Art'. *Energy Reports* 8, 1207–1228

Currie, W.L. (2004) ‘The Organizing Vision of Application Service Provision: A Process-Oriented Analysis’. *Information and Organization* 14 (4), 237–267

Du, J., Zhu, Q., Shi, Y., Wang, Q., Lin, Y., and Zhao, D. (2020) ‘Cognition Digital Twins for Personalized Information Systems of Smart Cities: Proof of Concept’. *Journal of Management in Engineering* 36 (2), 04019052

Ebrahimi, A. (2019) ‘Challenges of Developing a Digital Twin Model of Renewable Energy Generators’. in *2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)*, ‘2019 IEEE 28th International Symposium on Industrial Electronics (ISIE)’ [online] held June 2019. 1059–1066. available from <https://ieeexplore.ieee.org/document/8781529> [9 August 2024]

Enders, M.R. and Hoßbach, N. (2019) *Dimensions of Digital Twin Applications - A Literature Review*. [online] (Energy Institute). available from <https://knowledge.energyinst.org/new-energy-world/article?id=138063>

Energy Institute, E. (2023) *How Digital Twin Technology Is a Game Changer for Offshore Wind* [online] available from <https://knowledge.energyinst.org/new-energy-world/article?id=138063> [21 October 2024]

Fahim, M., Sharma, V., Cao, T.-V., Canberk, B., and Duong, T.Q. (2022) ‘Machine Learning-Based Digital Twin for Predictive Modeling in Wind Turbines’. *IEEE Access* 10, 14184–14194

Fang, X., Lin, S., Huang, X., Lin, F., Yang, Z., and Igarashi, S. (2018) ‘A Review of Data-Driven Prognostic for IGBT Remaining Useful Life’. *Chinese Journal of Electrical Engineering* 4, 73–79

Farjoun, M. (2010) *BEYOND DUALISM: STABILITY AND CHANGE AS A DUALITY*. Academy of Management Review

Faulkner, P. and Runde, J. (2013) ‘Technological Objects, Social Positions, and the Transformational Model of Social Activity’. *MIS Quarterly* 37 (3), 803–818

Fichman, R. (2004) ‘Going Beyond the Dominant Paradigm for Information Technology Innovation Research: Emerging Concepts and Methods’. *Journal of the Association for Information Systems* 5 (8), 314–355

Gawer (2009) *Platforms, Markets and Innovation*. available from <https://www.elgaronline.com/edcollbook/9781848440708.xml> [16 August 2024]

Giddens, A. (1979) *Central Problems in Social Theory: Action, Structure, and Contradiction in Social Analysis*. University of California Press

Global Wind Energy Council (2024) *Global Wind Report 2024* [online] available from <https://gwec.net/wp-content/uploads/2024/05/GWR-2024_digital-version_final-2.pdf> [9 August 2024]

Grosse, C.U. (2019) ‘Monitoring and Inspection Techniques Supporting a Digital Twin Concept in Civil Engineering: 5th International Conference on Sustainable Construction Materials and Technologies, SCMT 2019’. *Sustainable Construction Materials and Technologies* [online] 2. available from

<http://www.scopus.com/inward/record.url?scp=85078988852&partnerID=8YFLogxK> [9 August 2024]

Hu, W., Zhang, T., Deng, X., Liu, Z., and Tan, J. (2021) 'Digital Twin: A State-of-the-Art Review of Its Enabling Technologies, Applications and Challenges'. *Journal of Intelligent Manufacturing and Special Equipment* 2, 1–34

Hui, Y. (2016) *On the Existence of Digital Objects*. U of Minnesota Press

Iosifidis, N., Zhong, Y., Hu, B., Chen, B., Ran, L., Lakshminarayana, S., Jia, C., McKeever, P., and Ng, C. (2021) 'Reliability of Wind Turbine Power Modules Using High-Resolution Wind Data Reconstruction: A Digital Twin Concept'. in *2021 IEEE Energy Conversion Congress and Exposition (ECCE)*, '2021 IEEE Energy Conversion Congress and Exposition (ECCE)' [online] held October 2021. 3630–3637. available from <https://ieeexplore.ieee.org/abstract/document/9595095> [9 August 2024]

Jahanshahi Zeitouni, M., Parvaresh, A., Abrazeh, S., Mohseni, S.-R., Gheisarnejad, M., and Khooban, M.-H. (2020) 'Digital Twins-Assisted Design of Next-Generation Advanced Controllers for Power Systems and Electronics: Wind Turbine as a Case Study'. *Inventions* 5 (2), 19

Jari Kaivo, O., Kuusi, O., Knudsen, M.S., and Lauraéus, I.T. (2020) 'Digital Twin: Current Shifts and Their Future Implications in the Conditions of Technological Disruption'. *International Journal of Web Engineering and Technology* 15 (2), 170

Javaid, M., Haleem, A., and Suman, R. (2023) 'Digital Twin Applications toward Industry 4.0: A Review'. *Cognitive Robotics* 3, 71–92

Jiang, Y., Yin, S., Li, K., Luo, H., and Kaynak, O. (2021) 'Industrial Applications of Digital Twins'. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 379 (2207), 20200360

Kallinikos, J. (2005) 'The Order of Technology: Complexity and Control in a Connected World'. *Information and Organization* 15 (3), 185–202

Kirchhof, J.C., Michael, J., Rumpe, B., Varga, S., and Wortmann, A. (2020) 'Model-Driven Digital Twin Construction: Synthesizing the Integration of Cyber-Physical Systems with Their Information Systems'. in *Proceedings of the 23rd ACM/IEEE International Conference on Model Driven Engineering Languages and Systems*, 'MODELS '20: ACM/IEEE 23rd International Conference on Model Driven Engineering Languages and Systems' [online] held 18 October 2020 at Virtual Event Canada. ACM, 90–101. available from <https://dl.acm.org/doi/10.1145/3365438.3410941> [8 July 2024]

Kitchin, R. and Dodge, M. (2014) *Code/Space: Software and Everyday Life*. MIT Press

Künneke, R., Mehos, D.C., Hillerbrand, R., and Hemmes, K. (2015) 'Understanding Values Embedded in Offshore Wind Energy Systems: Toward a Purposeful Institutional and Technological Design'. *Environmental Science & Policy* 53, 118–129

La Grotta, A., Harris, R.L., and Da Costa, C. (2021) *Mooring Sense Project: A Risk-Based Integrity Management Strategy for Mooring System of Floating Offshore Wind*. in 'Abu Dhabi International

Petroleum Exhibition & Conference' [online] held 9 December 2021. OnePetro. available from <https://dx.doi.org/10.2118/207887-MS> [9 August 2024]

LeBlanc, B. and Ferreira, C. (2020) 'Experimental Characterization of H-VAWT Turbine for Development of a Digital Twin'. *Journal of Physics: Conference Series* 1452 (1), 012057

Leng, J., Wang, D., Shen, W., Li, X., Liu, Q., and Chen, X. (2021) 'Digital Twins-Based Smart Manufacturing System Design in Industry 4.0: A Review'. *Journal of Manufacturing Systems* 60, 119–137

Li, J., Qin, Z., Liu, W., and Yu, X. (2024) 'Energy-Aware and Trust-Collaboration Cross-Domain Resource Allocation Algorithm for Edge-Cloud Workflows'. *IEEE Internet of Things Journal* 11 (4), 7249–7264

Li, Y. and Shen, X. (2022) 'A Novel Wind Speed-Sensing Methodology for Wind Turbines Based on Digital Twin Technology'. *IEEE Transactions on Instrumentation and Measurement* 71, 1–13

Liu, M., Fang, S., Dong, H., and Xu, C. (2021) 'Review of Digital Twin about Concepts, Technologies, and Industrial Applications'. *Journal of Manufacturing Systems* 58, 346–361

MarketsandMarkets (2023) *Digital Twin Market Size, Share, Industry Report, Revenue Trends and Growth Drivers* [online] available from <https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html> [19 August 2024]

Mehlan, F., Pedersen, E., and R. Nejad, A. (2022) 'Modelling of Wind Turbine Gear Stages for Digital Twin and Real-Time Virtual Sensing Using Bond Graphs'. *Journal of Physics: Conference Series* 2265, 032065

Melnikovas, A. (2018) 'Towards an Explicit Research Methodology: Adapting Research Onion Model for Futures Studies'. *Journal of Futures Studies* 23, 29–44

Moghadam, H., Foroozan, H., Gheisarnejad Chirani, M., and Khooban, M.-H. (2021) 'A Survey on New Trends of Digital Twin Technology for Power Systems'. *Journal of Intelligent & Fuzzy Systems* 41, 3873–3893

Momber, A.W., Möller, T., Langenkämper, D., Nattkemper, T.W., and Brün, D. (2022) 'A Digital Twin Concept for the Prescriptive Maintenance of Protective Coating Systems on Wind Turbine Structures'. *Wind Engineering* 46 (3), 949–971

Nuñez-Montoya, B., Naranjo-Riofrío, C., López-Estrada, L., Tutivén, C., Vidal, Y., and Fajardo-Pruna, M. (2022) 'Development of a Wind Turbine Digital-Twin for Failure Prognosis: First Results'. in *2022 5th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)*, '2022 5th International Conference on Advanced Systems and Emergent Technologies (IC_ASET)' [online] held March 2022. 29–33. available from <https://ieeexplore.ieee.org/abstract/document/9765858> [9 August 2024]

Olatunji, O.O., Adedeji, P.A., Madushele, N., and Jen, T.-C. (2021) 'Overview of Digital Twin Technology in Wind Turbine Fault Diagnosis and Condition Monitoring'. in *2021 IEEE 12th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT)*, '2021 IEEE 12th International Conference on Mechanical and Intelligent Manufacturing Technologies

(ICMIMT)' [online] held 13 May 2021 at Cape Town, South Africa. IEEE, 201–207. available from <https://ieeexplore.ieee.org/document/9476186/> [8 July 2024]

Oñederra, O., Asensio, F.J., Eguia, P., Perea, E., Pujana, A., and Martinez, L. (2019) 'MV Cable Modeling for Application in the Digital Twin of a Windfarm'. in *2019 International Conference on Clean Electrical Power (ICCEP)*, '2019 International Conference on Clean Electrical Power (ICCEP)' [online] held July 2019. 617–622. available from <https://ieeexplore-ieee-org.esc-web.lib.cbs.dk/abstract/document/8890166> [9 August 2024]

Osmundsen, K.S., Meske, C., and Thapa, D. (2022) 'Familiarity with Digital Twin Totality: Exploring the Relation and Perception of Affordances through a Heideggerian Perspective'. *Information Systems Journal* 32 (5), 1064–1091

Pargmann, H., Euhausen, D., and Faber, R. (2018) *Intelligent Big Data Processing for Wind Farm Monitoring and Analysis Based on Cloud-Technologies and Digital Twins: A Quantitative Approach*.

Parmar, R., Leiponen, A., and Thomas, L.D.W. (2020) 'Building an Organizational Digital Twin'. *Business Horizons* 63 (6), 725–736

Parvaresh, A., Abrazeh, S., Mohseni, S.-R., Zeitouni, M.J., Gheisarnejad, M., and Khooban, M.-H. (2020) 'A Novel Deep Learning Backstepping Controller-Based Digital Twins Technology for Pitch Angle Control of Variable Speed Wind Turbine'. *Designs* 4 (2), 15

Qi, Q., Tao, F., Zuo, Y., and Zhao, D. (2018) 'Digital Twin Service towards Smart Manufacturing'. *Procedia CIRP* 72, 237–242

Rinaldi, G., Thies, P.R., and Johanning, L. (2021) 'Current Status and Future Trends in the Operation and Maintenance of Offshore Wind Turbines: A Review'. *Energies* 14 (9), 2484

Sahoo, R. (2017) *Strength of Shear Web with Circular Hole in Wind Turbine Blades and Using Digital Twining Concept to Reduce Material Testing* [online] available from <https://www.phindia.com/Books/BookDetail/9789354432958/indeterminate-structural-analysis-sahoo> [9 August 2024]

Salimbeni, S., Redchuk, A., and Rousserie, H. (2023) 'Quality 4.0: Technologies and Readiness Factors in the Entire Value Flow Life Cycle'. *Production & Manufacturing Research* 11

Saunders, M., Philip, L., and Thornhill, A. (2019) *Research Methods for Business Students.* [online] available from <https://www.pearson.com/en-au/media/gnqjwj0v/9781292402727_sample.pdf>

Schleich, B., Anwer, N., Mathieu, L., and Wartzack, S. (2017) 'Shaping the Digital Twin for Design and Production Engineering'. *CIRP Annals* 66 (1), 141–144

Sharma, A., Kosasih, E., Zhang, J., Brintrup, A., and Calinescu, A. (2022) 'Digital Twins: State of the Art Theory and Practice, Challenges, and Open Research Questions'. *Journal of Industrial Information Integration* 30, 100383

Shen, Z.-J.M., Wang, L., and Deng, T. (2021) 'Digital Twin: What It Is, Why Do It, and Research Opportunities for Operations Research'. *SSRN Electronic Journal*

Svendsrud, D.S. and Paparova, D. (2023) *Data Hierarchies: The Emergence of an Industrial Data Ecosystem*.

Swanson, E.B. (1994) 'Information Systems Innovation Among Organizations'. *Management Science* 40 (9), 1069–1092

Swanson, E.B. and Ramiller, N.C. (1997) 'The Organizing Vision in Information Systems Innovation'. *Organization Science* 8 (5), 458–474

Tilson, D., Sorensen, C., and Lyytinen, K. (2021) 'Digitally Induced Industry Paradoxes: Disruptive Innovations of Taxiwork and Music Streaming Beyond Organizational Boundaries'. in *Research in the Sociology of Organizations* [online] ed. by Bednarek, R., E Cunha, M.P., Schad, J., and Smith, W.K. Emerald Publishing Limited, 171–192. available from <https://www.emerald.com/insight/content/doi/10.1108/S0733-558X2021000073a013/full/html> [16 October 2024]

Tiwana, A., Konsynski, B., and Bush, A.A. (2010) 'Research Commentary—Platform Evolution: Coevolution of Platform Architecture, Governance, and Environmental Dynamics'. *Information Systems Research* 21 (4), 675–687

Tygesen, U., Jepsen, M., Vestermark, J., Dollerup, N., and Pedersen, A. (2018) *The True Digital Twin Concept for Fatigue Re-Assessment of Marine Structures*.

University of Wisconsin–Milwaukee, Nambisan, S., Lyytinen, K., Case Western Reserve University, Majchrzak, A., University of Southern California, Song, M., and Xi'an Technological University (2017) 'Digital Innovation Management: Reinventing Innovation Management Research in a Digital World'. *MIS Quarterly* 41 (1), 223–238

Van Der Valk, H., Haße, H., Möller, F., and Otto, B. (2022) 'Archetypes of Digital Twins'. *Business & Information Systems Engineering* 64 (3), 375–391

Wadhwani, M., deshmukh, S., and Dhiman, H. (2022) *Digital Twin Framework For Time To Failure Forecasting of Wind Turbine Gearbox: A Concept*.

Walker, J., Coraddu, A., Collu, M., and Oneto, L. (2022) 'Digital Twins of the Mooring Line Tension for Floating Offshore Wind Turbines to Improve Monitoring, Lifespan, and Safety'. *Journal of Ocean Engineering and Marine Energy* 8 (1), 1–16

Wanasinghe, T.R., Wroblewski, L., Petersen, B.K., Gosine, R.G., James, L.A., De Silva, O., Mann, G.K.I., and Warrian, P.J. (2020) 'Digital Twin for the Oil and Gas Industry: Overview, Research Trends, Opportunities, and Challenges'. *IEEE Access* 8, 104175–104197

Wang, Y., Ren, W., Li, Y., and Zhang, C. (2021) 'Complex Product Manufacturing and Operation and Maintenance Integration Based on Digital Twin'. *The International Journal of Advanced Manufacturing Technology* 117 (1), 361–381

Woitsch, R., Sumereder, A., and Falcioni, D. (2022) 'Model-Based Data Integration along the Product & Service Life Cycle Supported by Digital Twinning'. *Computers in Industry* 140, 103648

Wurm, B., Becker, M., University of Southern Denmark Denmark, Pentland, B.T., Michigan State University USA, Lyytinen, K., Case Western Reserve University USA, Weber, B., University of

St. Gallen Switzerland, Grisold, T., University of Liechtenstein Liechtenstein, Mendling, J., Humboldt-Universität zu Berlin, Berlin, Germany Vienna University of Economics and Business, Austria Weizenbaum-Institut, Berlin, Germany, Kremser, W., and Johannes Kepler Universität Linz Austria (2023) 'Digital Twins of Organizations: A Socio-Technical View on Challenges and Opportunities for Future Research'. *Communications of the Association for Information Systems* 52, 552–565

Xiangjun, Z., Ming, Y., Xianglong, Y., Yifan, B., Chen, F., and Yu, Z. (2020) *Anomaly Detection of Wind Turbine Gearbox Based on Digital Twin Drive*.

Xu, X., Lu, Y., Vogel-Heuser, B., and Wang, L. (2021) 'Industry 4.0 and Industry 5.0—Inception, Conception and Perception'. *Journal of Manufacturing Systems* 61, 530–535

Yaqub, M.Z. and Alsabban, A. (2023) 'Industry-4.0-Enabled Digital Transformation: Prospects, Instruments, Challenges, and Implications for Business Strategies'. *Sustainability* 15 (11), 1–33

Yoo, Y., Boland, R.J., Lyytinen, K., and Majchrzak, A. (2012) 'Organizing for Innovation in the Digitized World'. *Organization Science* 23 (5), 1398–1408

Yoo, Y., Henfridsson, O., and Lyytinen, K. (2010) 'Research Commentary—The New Organizing Logic of Digital Innovation: An Agenda for Information Systems Research'. *Information Systems Research* 21 (4), 724–735

Zammuto, R.F., Griffith, T.L., Majchrzak, A., Dougherty, D.J., and Faraj, S. (2007) 'Information Technology and the Changing Fabric of Organization'. *Organization Science* 18 (5), 749–762

Zhao, H., Hu, W., Liu, Z., and Tan, J. (2021) *A CapsNet-Based Fault Diagnosis Method for a Digital Twin of a Wind Turbine Gearbox*. in 'ASME 2021 Power Conference' [online] held 18 August 2021. American Society of Mechanical Engineers Digital Collection. available from <https://dx.doi.org/10.1115/POWER2021-66029> [9 August 2024]

Zuboff, S. (1988) *In the Age of the Smart Machine: The Future of Work and Power*. Heinemann Professional