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Augmented Reality Tooling for Field Technicians in Operations & Maintenance of Offshore Wind Farms

Technical Feasibility, Process Analysis, and Business Case

TU Delft

VATTENFALL

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By

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Executive Summary

This thesis investigates the potential of Augmented Reality (AR) headsets to enhance field technicians' performance (in terms of efficiency and effectivity) in Operations and Maintenance (O&M) processes in Offshore Wind Farms (OWF), with Vattenfall's operations serving as the case study. **The key deliverable of this report has been the Business Case (Chapter 9),** which provides a qualitative and quantitative analysis of the AR enhanced business process innovation**.** A critical gap for such empirical case studies was identified in the field of industrial AR applications, especially in offshore wind contexts, as noted in Chapter 1. The research is further motivated by the generation of a generalisable multi-framework approach for business process innovation. This approach evaluates the business case of novel technologies such as AR in capital-intensive industries, fitting in Vattenfall's (generalisable) Stage-Gate innovation model (Chapter 2). Furthermore, societal impact is granted through accelerating the energy transition, by providing the first step in a business process innovation that should lower the O&M costs (which is about 30% of the Levelized Cost of Energy (LCOE, full lifecycle cost) (Bosch et al., 2019)) of renewable energy, improving its competitiveness against fossil fuels (Chapter 2). This has led to the Research Question:

How may Offshore Wind Farm Operations and Maintenance activities within the organisational context at Vattenfall NL benefit from the enhanced performance promised by AR technology?

To address this question, the study employs a multi-method approach (Chapter 3) comprising:

- *Chapter 4 and 5:* A structured literature review (keywords + snowballing) combined with an AI enhanced literature expansion on AR applications in industrial maintenance and broader contexts.
- *Chapter 6:* Market analysis of tailored AR-enabled Field Service Management (FSM) platforms.
- *Chapter 7:* Semi-structured interviews with Vattenfall stakeholders.
- *Chapter 8:* Synthesis and evaluation of candidate processes suitable for AR enhancement according to the results of the above.
- ***Chapter 9:*** **Business Case** development using a combined framework of: Business Process Model Notation, Business Model Canvas, Value Proposition Canvas, Lean Six Sigma, and Financial Analysis. This is based on the insights from this research and publicly available financial data for a first-order estimation on the potential benefit of AR. **A novel adaptation of the Business Model Canvas on a business process innovation is presented.**

Results

The literature review (Chapter 4) and broader consumer, enterprise, and industrial applications (Chapter 5) confirm AR's technological maturity for industrial use, particularly as a decision support tool and in improving manual task completion time and reducing errors. AR solutions involve hands-free digital work instructions, immersive training, and remote expert support. However, empirical validation, especially in offshore contexts, remains limited, highlighting a critical gap in the academic literature (Chapter 1).

Market analysis identifies RealWear (headset) and OverIT (software) as field-ready solutions (Chapter 6). Stakeholder interviews reveal strong interest in AR for ad-hoc corrective maintenance workflows, particularly in reducing revisit frequency and improving first-time fix rates, though digital integration and user acceptance are identified as barriers (Chapter 7). Organisational feasibility is assessed using the Technology Acceptance Model (TAM), revealing high perceived usefulness but moderate ease of use and some operational barriers which need to be addressed, contingent on ergonomic design and privacy safeguards (Chapter 7).

Business Case (AI)

The key deliverable of this thesis is the Business Case presented in Chapter 9, which provides a qualitative and quantitative assessment of the proposed business process innovation. The most promising application identified in Chapter 8 is **Augmented Reality (AR)-enhanced Remote Expert Support**, enabling real-time, hands-free collaboration between field technicians and remote experts. This functionality enables remote experts to guide field technicians through complex procedures via live, bidirectional video communication. For instance, during ad-hoc troubleshooting, experts can interpret the technician's video feed in real time to assist with navigating service manuals and provide targeted information directly to the technician's headset. This allows technicians to remain hands-free and focused on the task, improving diagnostic accuracy, reducing procedural errors, and minimising the time spent consulting documentation.

The primary operational benefit of AR-enhanced Remote Expert Support lies in its potential to increase the **first-time fix rate** and reduce the frequency of subsequent turbine revisits during unplanned maintenance events. This is achieved through three mechanisms:

1. Preventing the creation of follow-up service requests ("tech tickets") by enabling more accurate troubleshooting during the initial intervention.
2. Improving the quality and completeness of tech tickets, thereby reducing the need for second or third visits due to missing or ambiguous information.
3. Facilitating targeted remote support during the first revisit, which can resolve outstanding issues and prevent further interventions. Collectively, these mechanisms contribute to reduced operational costs (fewer total visits) and turbine downtime (issues resolved earlier), with direct implications for Vattenfall's profitability as demonstrated in the financial modelling (Chapter 9).

The business case demonstrates strong alignment with Vattenfall's operational objectives, as evaluated through the **Business Process Model Notation (BPMN)**, **Business Model Canvas (BMC)**, **Value Proposition Canvas (VPC)**, and **Lean Six Sigma** frameworks. This multi-framework approach to evaluating a business process innovation confirms a high degree of organisational and (internal) customer fit (Chapter 9).

First-order cost savings estimation

Stakeholder interviews (Chapter 7) and Lean Six Sigma analysis (Chapter 9) identify revisit-related costs and turbine downtime as key sources of operational waste, which are mitigated through the implementation of AR enhanced remote expert support. Under median assumptions, the new process yields annual savings of approximately **€1.8 million per offshore wind farm**, with scenario outcomes ranging from negligible savings to a maximum of **€95 million**, depending on site-specific parameters.

Pilot study recommendation

The upper-bound scenario underscores the strategic importance of **pilot site selection**. Sites with high energy yield per turbine incur proportionally higher downtime costs, making operational performance gains more financially impactful. Additionally, a high frequency of ad-hoc maintenance events and revisit rates (often driven by complex or poorly documented faults) amplifies the potential value of AR-enhanced support. The effectiveness of AR systems is further increased in environments with high levels of digitalisation and structured asset information, which facilitate real-time expert guidance. These conditions are most commonly found in **newer wind farms employing novel turbine platforms**, suggesting that such sites are optimal candidates for pilot implementation and are likely to yield the most favourable return on investment.

The wide profitability bandwidth reflects significant uncertainty in key input parameters, key areas for future research towards further empirical validation of these metrics. This is a critical area for improvement of the business case prior to pilot deployment, as discussed in Chapters 10 and 11.

The proposed implementation aligns with Vattenfall's **Stage-Gate innovation framework**, supporting a structured progression from exploratory research to pilot testing and eventual full-scale deployment (Chapter 3, Figures 20–21).

Key Contributions to the Field and Vattenfall

The thesis contributes to academic literature by providing an empirical case study through the combined framework for AR adoption in offshore wind maintenance, addressing a previously underexplored application domain. The methodology provided is further generalisable towards novel technology applications in other capital-intensive industries. In summary:

- Addressing a critical gap in empirical AR research within offshore maintenance by providing an initial business case for AR in OWF O&M.
- Providing a structured methodology combining novel adaptations of proven frameworks in business analysis: Business Process Modelling Notation (BPMN), Business Model Canvas (BMC), Value Proposition Canvas (VPC), Leas Six Sigma (LSS), and Financial Analysis for evaluating emerging technologies in asset-intensive industries.
- A novel adaptation of the Business Model Canvas to describe a business process innovation rather than an entire business or product.
- Empirical insights from stakeholder interviews, synthesised in the frameworks of Technological and Organisational feasibility, Barriers to Entry, and TAM.
- Providing strategic recommendations for future researchers and Vattenfall.

Key Recommendation for Vattenfall

It also offers **actionable recommendations for Vattenfall,** including:

- Further financial modelling of offshore wind farm metrics combined with the suggested AR enhanced business process improvements in revisit frequency.
- Stakeholder engagement and change management.
- Integration planning with SAP/Salesforce systems.

- Pilot implementation of AR-enabled Remote Expert Support.
- Progress through the existing Stage-Gate development model accordingly.

In conclusion, AR's value lies in its ability to improve process efficiency. In the explored use case (OWF O&M), this means to increase activity accuracy, reduce revisit frequency and improve technician training, all of which directly impact operational efficiency and asset availability. The findings support the recommendation to proceed within the Stage-Gate framework towards pilot implementation, contingent on further validation of financial and organisational feasibility.

Nomenclature

Abbreviations

- **AI** – Artificial Intelligence
- **AR** – Augmented Reality
- **AWP** – Approved Work Procedure
- **BMC** – Business Model Canvas
- **BPMN** – Business Process Modelling Notation
- **CACAR** – Context Aware Cognitive Augmented Reality
- **CBA** – Cost-Benefit Analysis
- **FOV** – Field of View
- **FSM** – Field Service Management
- **HMD** – Head Mounted Display
- **HUD** – Heads Up Display
- **LLM** – Large Language Model
- **MTTR** – Mean Time to Repair
- **NPV** – Net Present Value
- **O&M** – Operations and Maintenance
- **OWF** – Offshore Wind Farm
- **QHSE** – Quality, Health, Safety and Environment
- **ROI** – Return On Investment
- **TAM** – Total Addressable Market
- **TAM** – Technology Acceptance Model
- **TRL** – Technology Readiness Level
- **VR** – Virtual Reality
- **WoW** – Way of Working

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1 Introduction

Since its inception as a tool for assembly technicians at Boeing in 1992 by Caudell & Mizell, 1992, Augmented Reality (AR) has transitioned from a speculative concept to a prominent technological frontier in mobile computing (Stefan Hall & Ryo Takahashi, 2017). Major technology firms are investing heavily in the development of versatile and sophisticated AR headset systems, such as the Microsoft HoloLens, Google Glass, Apple Vision Pro, and Meta Ray-Ban smart glasses. These companies are driving innovation through substantial R&D budgets, pushing the boundaries of what wearable AR devices can achieve. Their multi-sided business models are based on a **technology-push** strategy: developing advanced hardware and integrating it into their existing software ecosystems to create new market opportunities towards users and software developers through providing sheer technical capability (Egger et al., 2023). Most applications of these systems are focused on consumer and enterprise use cases, but some systems like the (discontinued) Microsoft HoloLens and the niche-focused RealWear systems are specifically focused on industrial use across energy, aerospace, healthcare, manufacturing, and logistics settings.

Figure 1: Can versatile AR systems be used in the context of the offshore wind industry? On the left: The Apple Vision Pro is a $3500 wearable Mixed Reality (XR) device. It seems to offer the most advanced and comprehensive quality and feature set currently (Apple Vision Pro, n.d.). 3rd party development seems to pick up, allowing more and more use cases for the technology as time progresses. On the right: AI-generated image of Offshore Wind Farm personnel performing Operations and Maintenance tasks (prompt: Make a picture with the apple device on the left, then an arrow pointing tot the right with a question mark in the

middle, pointing to a picture on the right showing an operational environment of offshore wind technicians working in an offshore wind farm).

1.1 Academic field synthesis

A structured review of publications in the field of industrial Augmented Reality (AR) applications shows a marked increase in research activity during the period of 2015 through 2025 (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025). This surge correlates strongly with rapid advancements in AR hardware and software platforms available on the market and the overall maturation of AR systems. Since Caudell and Mizell's foundational work in 1992, the past decade has seen a proliferation of studies in manual **assembly** tasks, and by extension in **industrial maintenance**, which often involves manual (dis)assembly.

In those industrial contexts, AR has shown technological capability and promise in **improved task efficiency, reduced error rates,** and **enhanced training** (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025). Parallel developments have also been documented in the context of **agriculture** (Sara et al., 2024) and **healthcare** (O'Callaghan, 2024, Egger et al., 2023, Patel et al., 2024, Seeliger et al., 2022, Rocco et al., 2024).

1.2 Gap in scientific literature

Despite this perceived technological maturity, the academic literature on AR remains predominantly speculative in highlighting AR's benefits. The literature synthesis presented in this thesis reveals a persistent emphasis on theoretical application frameworks and feature-level demonstrations, while **empirical validation** of AR systems beyond laboratory walls **is notably underexplored.** Perceived barriers to entry for AR systems such as ease of use are also consistently mentioned across literature, signalling risks in field applications with key user groups.

1.2.1 Empirical omission

Concludingly, the field indicates a **critical gap** between technological capability and **empirical studies on implementation.** This gap is also consistently identified in the recent literature reviews as a priority for future research, underscoring the need for in empirical studies that assess AR's effectiveness under operational conditions.

1.2.2 Offshore wind sector omission

This gap is especially pronounced in the Offshore Wind Farm (OWF) Operations and Maintenance (O&M) domain, which is the focussed field of application of this thesis. The OWF sector presents unique challenges, including harsh environmental conditions, logistical complexity, and stringent safety protocols, which are not adequately addressed in existing AR research. Although OWF O&M activities share procedural similarities with factory-based maintenance tasks, the literature offers few, if any, case studies validating AR's effectiveness in the OWF context., except for one paper with a very limited assessment of AR's effectiveness: Eggert et al., 2020.

1.2.3 Business case omission

Moreover, while qualitative benefits such as improved technician efficiency, accuracy and training are frequently cited, the absence of business case evaluations constitutes a critical omission. **Technology push alone is ineffective** without a justification for the end users beyond just novelty. The **technology adoption** of AR may stall with the absence of a sound economic justification, despite continued development. This cycle may continue, until the technology has matured enough to where the value proposition becomes so apparent technology pull starts to occur. Alternatively, the interest in development may halt since there is no perceived interest from the market in adopting the innovations.

1.3 Academic justification

This dynamic has been observed at Vattenfall, where previous investigations into AR for OWF O&M yielded inconclusive results and were ultimately suspended. The absence of known validated business cases throughout literature and industries hindered further investment, illustrating the broader challenge of transitioning AR from experimental promise to operational reality. In contrast, this thesis adopts a **technology-pull** perspective. Rather than beginning with the technology and seeking applications, the research starts with a real-world operational context and investigates how AR may be applied there. This thesis aims to fill the literature gap by developing a qualitative business case for AR-enhanced activities within Vattenfall's OWF O&M operations.

The academic contribution of this research lies not merely in its contribution to bridging the literature gap and providing a case study as requested by the scientific community, but also in presenting a generalisable methodology for evaluating novel applications in asset-intensive industries. By adopting a technology-pull perspective and grounding the investigation in Vattenfall's operational context, the study offers a novel empirical case that complements the existing theoretical models surrounding AR technology. It also contributes to the broader discourse on emerging technology adoption in asset-intensive industries, where evaluating practical feasibility, user acceptance and organisational fit are as critical as technical capability.

1.4 Research Outline

In contrast to most academic literature in the field, this research does not investigate whether AR is impressive, but rather if it is a useful productivity tool within a complex, asset intensive, operations-focused organisation. This leads to the central research question:

How may Offshore Wind Farm Operations and Maintenance activities within the organisational context at Vattenfall NL benefit from the enhanced performance promised by AR technology?

To address this question, the study employs a multi-method approach (further explained in Chapter 3) comprising:

- *Chapter 4 and 5:* A structured literature review (keywords + snowballing) combined with an AI literature expansion search on AR applications in industrial maintenance and broader contexts.
- *Chapter 6:* Market analysis of readily available, tailor-made AR-enabled Field Service Management (FSM) platforms for industrial use.
- *Chapter 7:* Semi-structured interviews with Vattenfall stakeholders on potential use cases, candidate processes and the perceived usefulness of AR in enhancing performance.

- *Chapter 8:* Evaluation of candidate processes suitable for AR enhancement according to the synthesised results of the above.
- *Chapter 9:* Business case development using a Business Process Model Notation, Business Model Canvas, Value Proposition Canvas, Lean Six Sigma, and Financial Analysis frameworks, given the available data synthesised in this research and publicly available financial data. **The adaptation of the Business Model Canvas on a business process innovation is novel.**
- *Chapter 10 and 11:* Discussion, Recommendations and Conclusion.

Ultimately, this thesis seeks to advance the research field and to support Vattenfall in making informed decisions about AR adoption by providing a structured assessment of AR's value proposition and operational feasibility in offshore wind O&M, supported by stakeholder insights and market analysis. By demonstrating the feasibility and value of AR in a complex operational setting through a business case, the research aims to catalyse further exploration, investment, and implementation, both within the offshore wind sector and other fields of application.

2 Background and Motivation

2.1 Social context

Renewable energy generation is already at a respectable market share worldwide, currently reaching an energy production share of 20% in select markets (Tian & Zhang, 2022, Hassan et al., 2024). Further growth in renewable power generation is needed to reach the International Energy Agency's 2050 net zero emission scenario, where up to 70% of electricity needs to be sourced from wind and solar energy production (IEA, 2021).

A key metric in achieving this transition is the Levelized Cost of Energy (LCOE), which reflects the total lifetime cost per kilowatt-hour of electricity generated. Grid parity (where renewable energy matches or undercuts the cost of fossil fuels) has been achieved in several markets (Tian & Zhang, 2022, Hassan et al., 2024, Motyka et al., 2018; Bosch et al., 2019). However, this milestone alone is insufficient. As the penetration of renewables grows, additional investments in grid infrastructure and energy storage become necessary to manage the variability of supply and demand. To remain competitive against fossil fuels, the LCOE of renewables must continue to decline to offset these secondary system costs.

Accounting for roughly 30% of the LCOE, **Operations and Maintenance (O&M**) is one of the largest cost drivers for Offshore Wind Farms over these assets' lifespans of 20-40 years (Tian & Zhang, 2022, Xia & Zou, 2023, Costa et al., 2021, Röckmann et al., 2017). Technological and process innovations that lower O&M costs are therefore critical. Reducing these costs not only enhances the economic viability of OWFs but also displaces fossil fuels in energy generation.

Augmented Reality (AR) is one such innovation with the potential to significantly reduce O&M costs by improving workflow performance. This underscores the societal relevance of this research and its potential contribution to a more sustainable energy future.

2.2 Vattenfall

Vattenfall is one of Europe's largest producers and retailers of electricity and heat, with nearly 19,000 employees and over a century of operational history. In 2024, the company reported 245 billion SEK (22 billion EUR) in sales and 33 billion SEK (3 billion EUR) in profit. Vattenfall is heavily investing in wind energy, with 14% of its 100 TWh annual generation coming from wind as of 2023. The 2024 Annual Report outlines plans to allocate 45% of its 170 billion SEK (15 billion EUR) capital expenditure to wind energy through 2029 (Vattenfall, n.d. (a), Vattenfall, n.d. (b), Vattenfall, n.d. (c)).

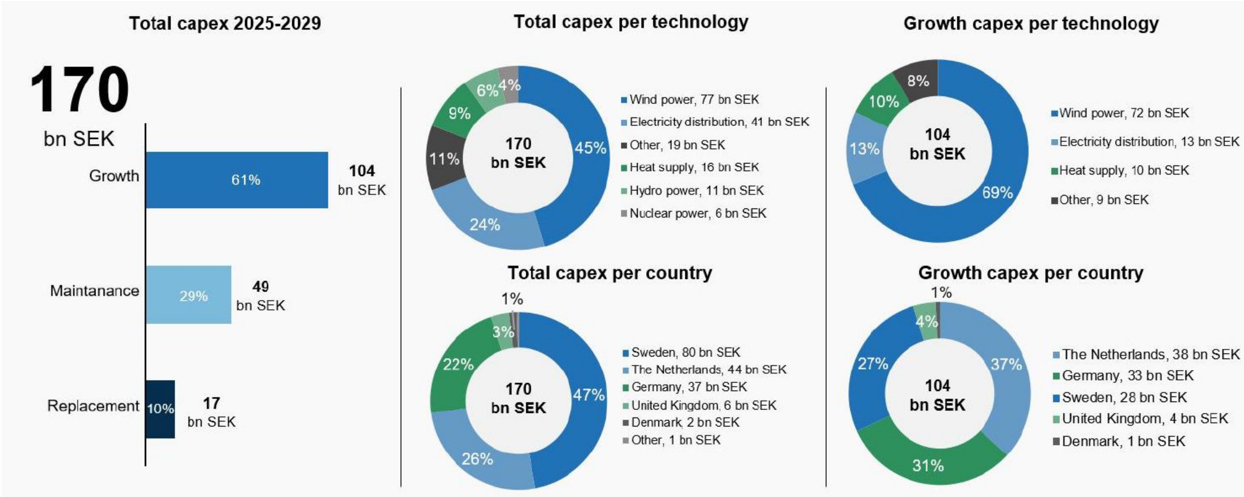

Figure 2: CAPEX from annual Report 2024 (Vattenfall, n.d. (c)).

As an operator of a large portfolio of wind farms, Vattenfall is actively exploring innovative technologies to enhance safety and efficiency in O&M activities. The O&M Product Lifecycle Management team, in collaboration with TU Delft, initiated this research to investigate the potential of AR in supporting these goals through a master thesis internship.

2.2.1 Product Lifecycle Management Team (Origin of the project)

This thesis is conducted in collaboration with Vattenfall's Product Lifecycle Management team within the Business Area Offshore Wind. The team evaluates market-available products that could improve OWF O&M activity performance, thereby lowering the LCOE of existing and new platforms, aiming to improve the competitive position of Vattenfall against competitors and fossil fuel alternatives.

For example, recent pilot projects include the use of cargo drones for tool and parts delivery from the supply vessel up to a turbine nacelle (sometimes 100m+ high). This solution provides clear value by saving mechanics time and reducing health and safety risks by reducing the need to climb ladders inside the turbine tower.

Vattenfall's previous investigation in AR seemed promising but remained inconclusive. The goal of this research is to provide more clarity on the value of the technology in Vattenfall's operational context, moving one step further towards pilot and implementation stages if confidence on a positive Return On Investment (ROI) is high enough.

2.2.2 Alignment with Vattenfall and TU Delft

This thesis is structured as a **product development advice** that bridges academic rigor with practical relevance. It aligns closely with both Vattenfall's product innovation governance and the MSc. Management of Technology (MOT) program at TU Delft. The MOT curriculum emphasizes the integration of technology, business, and policy; principles that are reflected throughout this research.

The study adopts an **exploratory** and **design-oriented approach**, which is appropriate given the relatively **low Technology Readiness Level (TRL)** of Augmented Reality (AR) for the targeted application in offshore wind farm operations and maintenance (O&M). Rather than delivering a fully validated solution, the research provides a **high-level assessment of AR's potential utility** within Vattenfall. It focuses on identifying a suitable workflow or process where AR could add value, developed into a business case.

This business case serves two purposes: first, as a communication tool to support internal decision-making on whether to invest further in AR development; and second, as a case study that contributes to the scientific literature on emerging technology implementation in asset-intensive industries.

The thesis mirrors the internal practices of Vattenfall's Product Lifecycle Management team, where team members evaluate and report on promising technologies for potential integration. This team uses the Technology Stage-Gate approach to innovation management (Figure 3, Figure 28), which is completely in line with usage throughout other industries. For example, for this low TRL technology, the initiation stage (PG1) has already been completed, and therefore it is appropriate **this thesis focuses on** (partially) fulfilling **the analysis phase** objectives and deliverables to advance through the current stage towards the next gate (PG2). By combining theoretical insights with practical application, the research not only fulfils academic requirements but also delivers actionable recommendations for Vattenfall. The deliverables, such as the business model and implementation framework, are intended as starting points not only for internal discussions and strategic planning but also for future researchers.

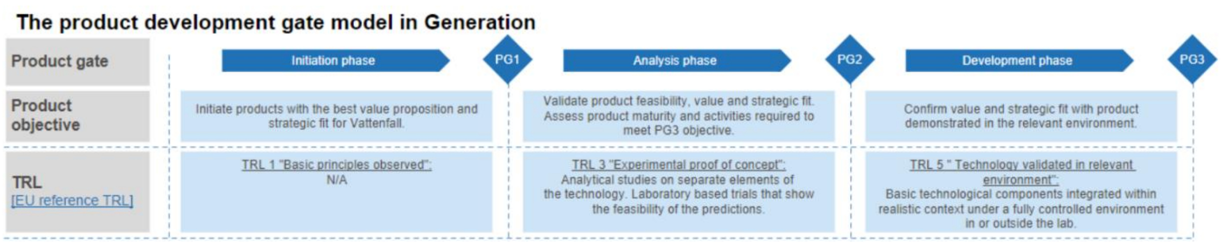

Figure 3: Vattenfall's Stage-gate model is similar to those found throughout industry (Vattenfall Internal SharePoint Document). It forms a system where limited technology trials are permitted, and, if successful, allows confidence to grow and progression through next stages and increased investment. Later stages are found in Appendix G.

3 Research Outline, Methodology and Scope

3.1 Research Objective

This research aims to explore the potential of Augmented Reality (AR) to enhance Operations and Maintenance (O&M) processes in offshore wind farms, with a specific focus on **Vattenfall's** operational context as a case study. The objective is to identify candidate processes within Vattenfall where AR could add value, assess the technical and organisational feasibility of implementation, and develop a business case to support decision-making.

Scientific literature and advancements in AR technology since 2015 show high potential and readiness for the usage of AR in manufacturing and maintenance tasks. However, literature focuses mainly on theoretical benefits and lab settings, while practical implementations remain limited due to the low market penetration of the technology and a lack of empirical case studies as noted in several literature reviews (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025). The technology does seem ready for the use cases indicated in the literature, with manual assembly and maintenance tasks seemingly benefitting the most from AR enhancement, but the market may not be ready yet.

Given the relatively low Technology Readiness Level (TRL) of AR for this specific application, the study is positioned at the **early exploratory stage** of Vattenfall's **Stage-Gate product development Way of Working (WoW)** (see Figure 3). At this stage, the goal is not to deliver a fully validated solution, but to provide a structured assessment of the opportunity space, including potential value for stakeholders, technical and organisational fit, and barriers to adoption. The deliverables are intended to serve as a **starting point for internal discussion**, and guidance for further development and investment within Vattenfall and the scientific field.

The research is also designed to align with the **TU Delft MSc. Management of Technology (MOT)** programme, which emphasises the integration of technology, business, and policy perspectives. The thesis applies MOT principles by combining:

- **Technology assessment** (e.g. TRL, feasibility, integration).
- **Business modelling** (e.g. business model canvas, value proposition, impact analysis).
- **Organisational alignment** (e.g. organisational fit, stakeholder needs, implementation barriers).

This dual alignment ensures that the research is both academically rigorous and practically relevant. It reflects the MOT programme's emphasis on innovation management by bridging the gap with emerging technologies and real-world implementation, particularly in complex, asset-intensive industries like offshore wind.

3.2 Deliverables and Scope

Based on the research' insights, the **final deliverable** will be an advice for future development, implementation and/or scale-up strategies for Vattenfall and future researchers. These outcomes of this research can be utilised by Vattenfall management to decide whether or not to pursue further (advised) steps for implementation of AR in the candidate processes. The insights and recommendations of this research also form a useful addition to the field of Augmented Reality, where there is currently a lack of case studies on practical implementations of the technology, its benefits, and weaknesses. This should hopefully help give direction to further research efforts and technological innovation.

As a design study, the scope of this research is intentionally focused and exploratory, which is aligned with the stage-gate approach for the TRL for this application. It does not aim to deliver a fully deployable AR solution, but rather to:

- Provide a clear overview of current **AR capabilities**
- Identify high-potential O&M **processes** at Vattenfall that could benefit from AR
- Evaluate the **technical feasibility** and **organisational readiness** for AR adoption
- Develop a **framework of requirements** for successful AR implementation
- Find the **barriers to entry**, and provide solutions as far as known.
- Provide a qualitative and, where possible, quantitative **impact assessment**
    - I.e. analyse the **benefits,** such as the potential for AR to eliminate inefficiencies (or 'waste' in LEAN terms) in said processes. How does this affect the bottom line, and by how much?
    - And the **costs,** such as singe occurrence implementation costs and recurring maintenance and support costs.
- Summarise findings in a **business case** format suitable for decision-making in Vattenfall

This scope fits the goals and deliverables of the Product Lifecycle Management team at this stage of development for the AR solution within Vattenfall's organisation. This also aligns with the Management of Technology coursework regarding the stage-gate development model for a low TRL solution. The research delivers on the scope in an academic context.

3.3 Research Question

How may Offshore Wind Farm Operations and Maintenance activities within the organisational context at Vattenfall NL benefit from the enhanced performance promised by AR technology?

3.3.1 Sub Questions

This leads to a set of sub questions which are answered throughout the research:

1. What are the current capabilities of AR technologies?
   This indicates how AR works to increase process efficiency (Chapter 4 and 5).
2. What are examples of successful AR implementations (in similar and other industries)?
   Further indicating AR capabilities in a broader context, leading to unique insights (Chapter 4 and 5).
3. What hardware, software, and services are available to support AR in industrial settings?
   Showcasing whether directly available market solutions are available for use in this context (Chapter 6).
4. What are the key O&M processes suitable for AR enhancement?
   For generating the best possible business case for AR enhancement, suitable processes are investigated through stakeholder interviews (Chapter 7) and evaluated in a structured manner (Chapter 8).
5. How should the process be changed to support AR?
   Synthesising how can AR be applied to the process to have a positive impact (Chapter 8).

6. What are the specific requirements for AR in offshore wind O&M processes?
   Indicating requirements and barriers to entry helps shape the business case development (Chapter 7).
7. What are the technical and organisational barriers to AR adoption?
   Indicating requirements and barriers to entry helps shape the business case development (Chapter 7).
8. What framework of requirements must be met for AR to be viable in the candidate application?
   And shaping the business case accordingly (Chapter 9).
9. What is the potential financial and operational impact of AR implementation?
   For supporting future development, the business case must organisationally work and be financially viable (Chapter 9).

3.4 Methodology Overview

To ensure the research objective is delivered, the research follows a structured, phased approach in answering the research questions:

1. Value Discovery

- Literature review on AR in Industrial / O&M context *(Chapter 4).*
- Analysis of practical AR implementations in other industries *(Chapter 5).*
- Market analysis on AR solutions offered in industrial and offshore contexts *(Chapter 6).*
- Identification of candidate O&M processes at Vattenfall through semi-structured interviews *(Chapter 7).*
- Definition of AR system requirements and barriers *(Chapter 7).*

2. Value Assessment

- Assessment of current AR capabilities against operational requirements *(Chapter 8).*
- Selection of best suitable process for further investigation *(Chapter 8).*
- Development of a business model for the selected process enhanced with AR *(Chapter 9).*
- Impact assessment (qualitative and first-order quantitative) *(Chapter 9).*

3. Business Case Development

- Synthesis of findings into a business case *(Chapter 9).*
- Recommendations for next steps in Vattenfall's Stage-Gate process *(Chapter 9, 10, 11).*
- Recommendations for future researchers / 'market ask' to increase TRL *(Chapter 10, 11).*

3.5 Stage-Gate Framing of Hypotheses and Expected Outcome

Although the present study is primarily qualitative in nature, statistical reasoning is employed to structure the research outcomes within a hypothesis-testing framework. This approach is particularly useful in aligning the research within Vattenfall's Stage-Gate innovation management model (see Chapter 2), which necessitates a binary decision-making structure: either to proceed with implementation (**Go**) or to suspend further development (**No-Go**). The use of statistical notation, Null Hypothesis **(H0)** and Alternative Hypothesis **(Ha),** serves to formalise this decision-making process and to clarify the expected direction of the findings based on the preliminary literature review (as presented in Chapter 1) and the initial interview (Appendix A, summarised in Chapter 7).

In classical statistical methodology, hypothesis testing involves the formulation of a **Null Hypothesis (H0)** and an **Alternative Hypothesis (Ha)**. The null hypothesis represents the default assumption, while the alternative hypothesis posits a deviation from this baseline. The decision to accept or reject the null hypothesis is based on whether the observed data provide sufficient evidence to conclude that the deviation is statistically significant, according to predefined criteria such as a significance level (such as alpha= 0.05).

Although this study does not employ inferential statistical testing due to its qualitative nature, the logic of hypothesis evaluation remains applicable. If the empirical findings provide sufficient support for the null hypothesis, it is retained, and the alternative hypothesis is rejected. Conversely, if the evidence contradicts the null hypothesis, it is rejected in favour of the alternative.

- **Null Hypothesis (H_0):** AR offers operational value in its current state for the selected O&M processes at Vattenfall. The integration of wearable AR systems is expected to enhance process performance and is also applicable to offshore capital-intensive contexts. If supported by the evidence, this outcome would justify progression towards refinement of the business case and pilot testing. Researchers within this field of study should focus on more empirical studies, expanding the application scope (in terms of processes and industries) and addressing identified technological, organisational and user limitations.
- **Alternative Hypothesis (H_1):** Augmented Reality (AR) does not offer sufficient operational value in its current state for the identified O&M processes. Either the identified processes are unsuitable towards AR enhancement, or AR's technological maturity is inadequate, the organisational readiness is insufficient, or the cost-benefit ratio does not justify implementation. The research naturally provides a detailed overview of the identified barriers to adoption. This outcome would warrant suspension or redirection of development efforts, with recommendations for future investigation aimed towards Vattenfall and researchers alike.

3.5.1 Role of Hypothesis Framing

This structured reasoning mirrors the binary decision structure of the Stage-Gate model and supports the **Product Gate 2** decision (see Figure 3), where empirical evidence is used to determine whether the innovation should progress to the next stage or be suspended. The approach ensures that the findings of the study are interpreted considering these hypotheses to inform the gate decision, **without presupposing the outcome.**

The hypothesis framework serves several methodological functions within this research:

1. **Structuring the Evaluation Criteria:** It enables the formulation of clear evaluation criteria for assessing AR's feasibility, including technical capability, organisational fit, and financial viability.
2. **Facilitating Qualitative Impact Assessment:** It provides a conceptual framework for interpreting stakeholder interviews, literature synthesis, and market analysis in terms of supporting or refuting the null hypothesis.
3. **Supporting Scenario Analysis:** It guides the development of qualitative analyses in Chapter 9, where the financial impact of AR implementation is modelled under varying assumptions.

4. **Aligning with Stage-Gate Governance:** It mirrors the binary decision logic of Vattenfall's Stage-Gate model, where technologies are either advanced to the next development phase or suspended based on structured evaluation.
5. **Enabling Future Quantitative Validation:** While this study does not perform statistical testing, the hypothesis structure lays the groundwork for future business case refinements and pilot studies where quantitative metrics (identified in Chapter 9) can be statistically evaluated.

3.6 Literature, Technology and Market Research Methodology

To ensure a comprehensive and academically rigorous foundation for this research, a structured and multi-modal literature review methodology is employed. The review aims to identify the following across three chapters:

- **Scientific literature:** *Chapter Literature Review: AR in Industrial Operations & Maintenance*:
  A structured literature review is conducted to assess the current state-of-the-art in Augmented Reality (AR) applications within industrial maintenance contexts, with a particular focus on Offshore Wind Farm Operations & Maintenance (OWF O&M). This review combined traditional academic search techniques **(keyword-based queries and snowballing)** with **AI-enhanced literature expansion,** as explained below.

- **Technological capability:** *Chapter State-of-the-AR: Capabilities and Market Landscape*:
  A cross-sectoral overview of advanced AR systems and applications is compiled to illustrate the maturity, diversity, and capability range of AR technologies. This review extended beyond the scope of offshore wind to include aerospace, medical, and consumer- / enterprise-grade systems. This is performed mostly using a **general internet search** to find the latest market developments, supported by a **structured literature review (keywords + snowballing)** where applicable.

- **Tailored market solutions:** *Chapter Market Analysis: AR* :
  A targeted market analysis is performed to identify AR-based software and hardware solutions relevant to Field Service Management (FSM) in industrial contexts. While the offshore wind sector presents unique operational challenges (remote locations, harsh weather, and high safety standards), these are shared by broader energy and offshore sectors. This expanded scope enabled the identification of capable and applicable solutions beyond the immediate domain. Furthermore, it provides academical relevance, as it shows use cases and service providers that are mostly absent from literature. Concludingly, potential suppliers for an implementation within Vattenfall are provided. This is performed using a **general internet search** as well as an **AI expanded search** to identify any further service providers and application fields.

3.6.1 Search Strategy for Scientific Research

The primary literature review was conducted using the following academic databases: IEEEXplore, ScienceDirect and Google Scholar. These platforms were selected for their extensive coverage of peer-reviewed publications in engineering, technology management, and industrial operations.

3.6.1.1 Keywords and Boolean Operators

The following keywords were used in various combinations with Boolean operators to refine the search:

- “Augmented Reality” AND (“Industrial Maintenance” OR “Operations and Maintenance” OR “O&M”)
- “Augmented Reality” AND (“Offshore Wind Farms” OR “Offshore Wind” OR “OWF”)
- “Augmented Reality” AND (“Offshore Wind Farms” OR “Offshore Wind” OR “OWF”) AND (“Operations and Maintenance” OR “O&M”)

3.6.1.2 Snowballing Technique

Backward and forward citation tracking was employed to identify additional relevant studies. Literature review studies such as (Runji et al., 2023), (Ong et al., 2023), (Malta et al., 2023), (Palmarini et al., 2018), (Behzadan et al., 2015), (Bottani & Vignali, 2019), (Fang et al., 2025) were especially helpful in providing a synthesised overview of the field. The review studies also cite a wide range of essential references, some of which have been included in this study such as (Caudell & Mizell, 1992), which is a foundational piece in the AR field and cited by many (751 times in papers and 69 times in patents). This technique proved particularly useful in locating foundational works and emerging applications not captured by keyword searches alone.

3.6.2 Review Scope, Inclusion and Exclusion Criteria

The literature review focused on empirical studies, technology assessments, and implementation frameworks. Particular attention was given to literature addressing AR’s impact on technician performance, error reduction, training effectiveness, and barriers to adoption in asset-intensive industries.

Included studies in Chapter 4 were almost exclusively published between 2015 and 2025, reflecting the period during which AR technologies matured significantly. However, with the snowballing technique, some essential study outside this timeframe is also included (Caudell & Mizell, 1992). Not only peer-reviewed journal articles, conference proceedings, and institutional reports were considered. Studies focusing solely on Virtual Reality (VR), consumer applications, or entertainment use cases were excluded unless they provided transferable insights into AR system capabilities for the industrial maintenance context, or as a showcase for technology maturity which is captured in *Chapter State-of-the-AR: Capabilities and Market Landscape.*

3.6.3 General Internet Search for State-of-the-Art AR Applications

In addition to peer-reviewed sources into AR usage for alternate domains, a general internet search was conducted to map the broader landscape of AR applications in both industrial and non-industrial domains. This included:

- Military-grade AR systems (e.g., F-35 fighter jet helmet).
- Medical telesurgery platforms (similar workflows, not AR enhanced yet in the field but an excellent candidate according to literature (Marescaux et al., 2002, Seeliger et al., 2022, Egger et al., 2023, O’Callaghan, 2024).
- Consumer / enterprise-grade AR/MR devices, why they are successful and why they may have failed to gain market traction (e.g., Apple Vision Pro, Meta Quest, Microsoft HoloLens).

Although (some of) these sources are not peer-reviewed and are not directly applicable to offshore wind O&M, they are included in *Chapter State-of-the-AR: Capabilities and Market Landscape* to illustrate the maturity, diversity, and capability range of AR systems. These examples serve to:

- Showcase the technical feasibility of AR in high-stakes environments.
- Provide insights into user interface design, system integration, and ergonomics.
- Expand the creative solution space for the offshore wind context by analogy.

Furthermore, an aimed internet search was performed to identify fitting market solutions of AR enhanced Field Service Management tools. These systems represent the practical implementation of AR technologies in industrial service contexts and were evaluated for their applicability to offshore wind O&M in Chapter 6.

3.6.4 AI-Enhanced Literature Exploration

An emerging scientific field, **Prompt Engineering** (Giray, 2023), (Chen et al., 2025) serves as a novel tool for academic research and writing and has been used throughout this study, including the enhancement of the literature exploration.

To augment the traditional search process, an AI-based Large Language Model (LLM) tool (Microsoft M365 Copilot) was employed for sparring, blind spot analysis, and literature expansion. This helped to:

- Identify underrepresented themes and emerging trends in AR deployment.
- Expansion of the literature base beyond conventional keyword limitations.
- Cross-reference findings across disciplines (aerospace, healthcare, manufacturing, logistics).

This approach ensured that the literature review was not only exhaustive but also strategically broadened to include adjacent domains with transferable insights. Keeping in mind the limitations of prompt engineering, all AI-generated suggestions were critically reviewed by the researcher for the method's pitfalls ((Giray, 2023), (Chen et al., 2025)), academic relevance, methodological rigour, and contextual applicability before inclusion in the thesis. For a reflection on the usage of AI tools within this research, see *Chapter Artificial Intelligence* .

3.6.5 Methodology justification

This broader perspective supports the thesis' exploratory and design-oriented approach. By combining structured academic review, AI-enhanced exploration, and market analysis, the research is both exhaustive and targeted, providing depth and breadth for a robust academic foundation for the subsequent analysis, stakeholder interviews and business case development.

3.7 Interview Methodology

Semi-structured interviews were performed with Internal Vattenfall Stakeholders with a wide variety of backgrounds and responsibilities. The aim was to elicit expert stakeholders on how AR technology might provide value for Vattenfall processes from a wide variety of views.

A semi-structured approach was chosen, so as to steer the conversation towards the topic of AR but leave room for open and honest answers from the point of view and current knowledge of the interviewee. The aim of this more open approach is to limit the amount of bias interviewees might receive from a heavily scripted interview, which may steer towards a certain train of thought. Since AR technology is relatively immature as it comes to field implementations and is not implemented within Vattenfall yet, it is expected that interviewees have little knowledge on the technology beyond the basic high-profile consumer products that are starting to become more heavily marketed in the mass-market. Therefore, there is expected to be some bias towards this technology from an industrial stakeholder point of view, since the AR systems they are probably familiar with are focused on mass-market consumers, which may seem gimmicky when viewed from an industrial process viewpoint.

Nonetheless, there were a few basic questions and statements within each interview that served as a starting point for the conversation, as a probe for the interviewees' knowledge on AR systems (in general, and in an industrial setting), and as a quick introduction to my research objectives as well as a quick overview of the current state of the art in AR. Then, the conversations were quickly steered towards the **<u>expert opinion</u>** of the interviewees on the AR subject, its **perceived added value** and their **perceived drawbacks** and **perceived barriers to entry.**

Then, usually there was some focus on brainstorming: with the current (and through the interview slightly updated / biased) knowledge on AR systems, the interviewees were asked which processes that they know of (within their own work of that of colleagues) might benefit the most from by AR. This usually gave two outputs:

1. The processes within Vattenfall that are suitable to AR enhancement
2. Leads towards other potential interviewees who may be key stakeholders: working with AR / the mentioned processes / key knowledge holders

Through a deep dive in the proposed processes, additional knowledge was gathered on the interviewee's opinion on the following:

1. What are the current problems with the process you mentioned?
2. How might AR solve these problems in your view?
3. What does the AR system need to do (functional requirements)?
4. What does Vattenfall need to do to integrate this AR system (organisational fit)?
5. What barriers to entry are there for implementing this proposed solution do you reckon?

3.7.1 Methodology strengths and limitations

While the number of interviews (five) may appear limited, each was selected purposefully and provides rich insights from a wide range of roles. Interviewees were identified primarily through referrals, with each participant having relevant experience either with AR technologies or with operational processes potentially suitable for AR enhancement. This approach prioritised depth over breadth, as appropriate for a low TRL assessment. Nonetheless, it is acknowledged that five interviews do not capture the full diversity of perspectives within Vattenfall. Furthermore, as some interviewees were already familiar with AR initiatives and others were not as well acquainted with the technology before the meeting, there is potential bias present in the answers of each. The interviews are therefore interpreted as indicative of Vattenfall stakeholder views rather than exhaustive and are used to complement findings from the literature review and market analysis.

4 Literature Review: AR in Industrial Operations & Maintenance

This literature review explores application of AR for technicians in offshore wind farm (OWF) operations and maintenance (O&M) and whether it is indeed effective in improving process performance. Research interest goes towards empirical research and case studies, if available, in order to assess the technological capabilities, maturity and applicability to this sector.

4.1 Introduction to Augmented Reality (AR)

Augmented Reality (AR) is a **decision support tool** that overlays digital content, such as images, instructions, data, or 3D models, onto the physical world in real time. Unlike **Virtual Reality (VR)**, which immerses users in a fully digital environment, AR enhances the real world by integrating digital elements through devices like smartphones, tablets, and increasingly, smart glasses and headsets. While smart glasses are more user comfortable to wear, headsets offer more functionality. An advanced AR headset system is shown in Figure 1, Figure 13, Figure 4, and a training application using that headset in Figure 7.

Figure 4: Apple Vision Pro user experience: In AR mode, 3D elements are projected upon the video feed of the real world you are sitting in. This enables Remote Collaborative immersive applications such as a game of chess with another person. The other (remote) person's avatar (realistic 3D scan of their face) and hands are projected real time in your AR space (Apple Vision Pro, n.d.).

Modern AR systems support both traditional (keyboard, mouse) and hands-free (voice, eye, gesture) inputs, enabling real-time interaction and contextual guidance with the task at hand and (remote) coworkers. AR headsets can be used by consumers for gaming or by office workers for remote collaboration and enabling a feeling of 'presence' of coworkers (see Figure 4). AR systems can also provide a traditional but more immersive ‘spatial computing’ experience, even while travelling (see Figure 13). These features make AR particularly suitable for industrial applications such as maintenance, training, and remote support, where displaying contextual information, situational awareness and operational efficiency are critical.

AR is increasingly used across industries such as manufacturing, healthcare, education, and maintenance. AR systems are mostly used to provide real-time data visualization, and interactive training by delivering context-aware information and annotations precisely when and where it is needed in the user’s field of view. **According to literature and marketing materials** (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025) and Chapter 6, this enhances user performance, reduces errors, and improves operational efficiency.

The core components of an effective AR system include:

- Seamless integration of real environments with virtual, contextual content
- Real-time, context-aware interaction between user, environment, and digital content
- Hands-free operation via wearable devices, including gesture / eye gaze / voice inputs

4.2 Technological Maturity and Capabilities

Augmented Reality (AR) has been a research topic for over three decades, since 1992 (Caudell and Mizell, 1992). This first implementation at Boeing in 1992 assisted mechanics in aircraft engine assembly and maintenance by showing wire schematics (Malta et al., 2023).

Since then, Augmented Reality (AR) has gained significant attention as a transformative tool in industrial maintenance, offering the potential to enhance technician performance, reduce downtime, and improve safety. Advancements in hardware and software since 2015 have enabled more robust and portable AR systems. These include smart glasses and head-mounted displays (HMDs), mobile AR platforms, and mixed reality devices capable of overlaying digital content in real time (see Figure 5 and Figure 6). Review studies such as Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025 highlight the growing maturity of AR, noting improvements in occlusion handling, field of view, and user interaction, which are critical stepping stones for product maturity.

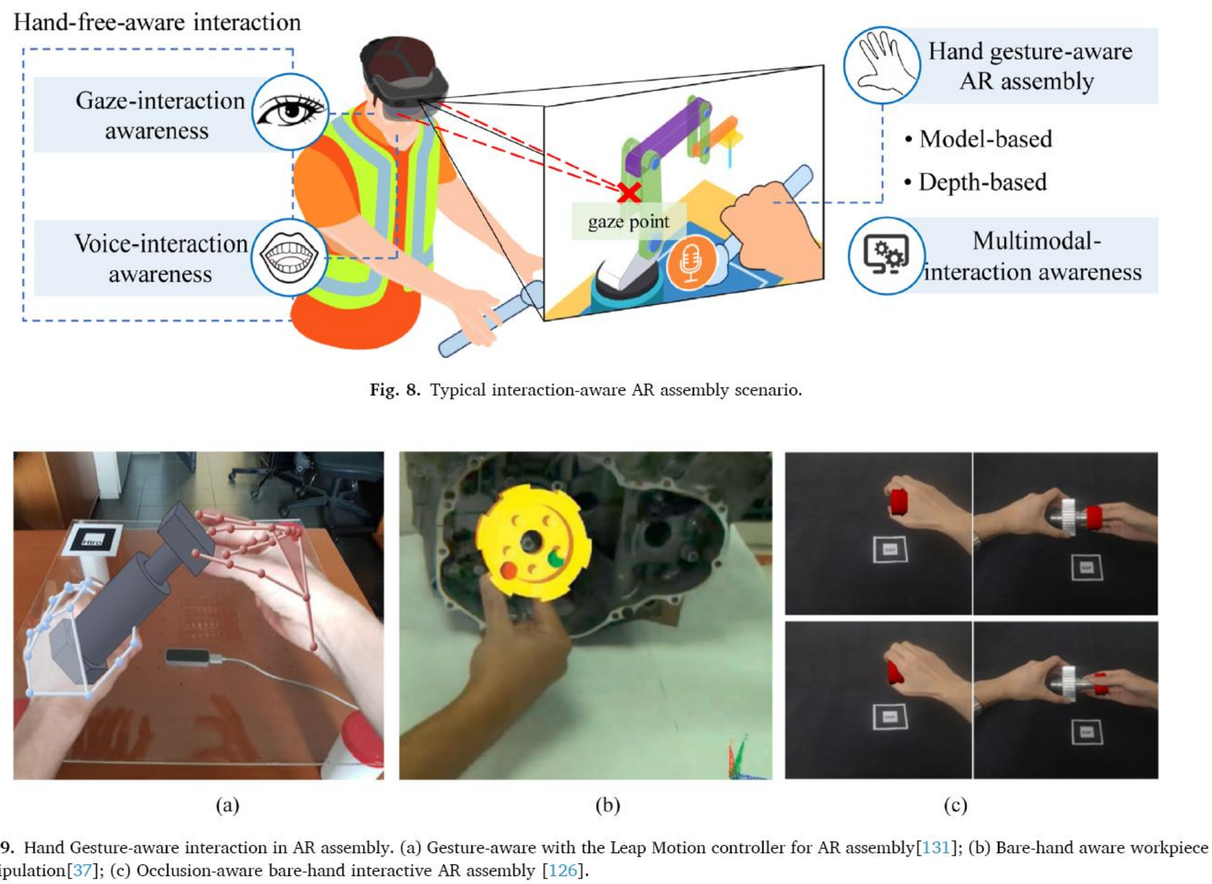

Figure 5: Image from Fang et al., 2025 highlighting the utility of AR for manual assembly tasks.

Ong, Siew, and Nee (2023) highlight that AR is increasingly capable of supporting complex maintenance tasks by overlaying digital information in real time, reducing reliance on paper-based manuals and improving situational awareness. These systems now integrate with IoT sensors, cloud platforms, and Enterprise Resource Planning (ERP) software such as SAP, enabling digital AR work instructions, real-time diagnostics, and remote collaboration **within existing organisational contexts.**

However, the maturity of AR varies significantly across sectors. While the potential benefits of Augmented Reality (AR) are well-documented in academic literature, and consumer-grade solutions have shown great functionality, its readiness for industrial deployment, particularly in offshore environments, remains underexplored as highlighted throughout and synthesised from all review studies (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025). Mourtzis et al. (2020) emphasize that many AR systems are limited to predefined scenarios and lack the flexibility required for dynamic, real-world maintenance tasks. However, one could argue that a paper-based service manual also does not add much in terms of flexibility in case an undocumented repair is needed. Most studies to date focus on theoretical advantages or lab-based demonstrations, with limited empirical validation in field settings (Fang et al., 2025).

This then leads to the motivation of this research: to find a practical case study for the application of AR. This gap in practical application forms the core motivation for this thesis: to explore the feasibility and value of AR in offshore wind farm (OWF) operations and maintenance (O&M), using Vattenfall as a case study to form a business case.

4.3 Benefits for Industrial Use Cases

For industrial tasks, AR has the potential to reduce the time required for and the error rate in completing tasks. Usually, positive impressions are given to the AR solution in terms of effectiveness and ease-of-use (Bottani and Vignali, 2019).

Literature focuses in particular on enhancing manual assembly workflows, which has close synergies to maintenance tasks. The literature identifies several high-potential AR applications in industrial settings, particularly in manufacturing, assembly, and maintenance. These include:

- **Hands-free Digital Work Instructions**: AR can deliver step-by-step guidance directly in the technician's field of view, reducing cognitive load and error rates (Ong et al., 2023), (Eggert et al., 2020).
- **Training and Knowledge Transfer**: AR enables immersive training environments (see Figure 7) and the creation of reusable content through video logging and simulation (Pasquale et al., 2024).
- **Remote Expert Support**: Real-time video feeds with annotations allow (office based) experts to guide (field) technicians remotely, reducing travel costs and improving first-time fix rates while increasing expert availability across sites (Mourtzis et al., 2020), (Fang et al., 2025).

4.3.1 Digital Work Instructions

These capabilities align closely with the needs of offshore wind O&M, where technician efficiency, safety, and access to expert knowledge are critical. Specifically, Head Mounted Display AR allows for hands-free step-by-step working instructions to be displayed to the technician, ensuring work accuracy, and decreasing errors. This helps ensuring no procedures are missed.

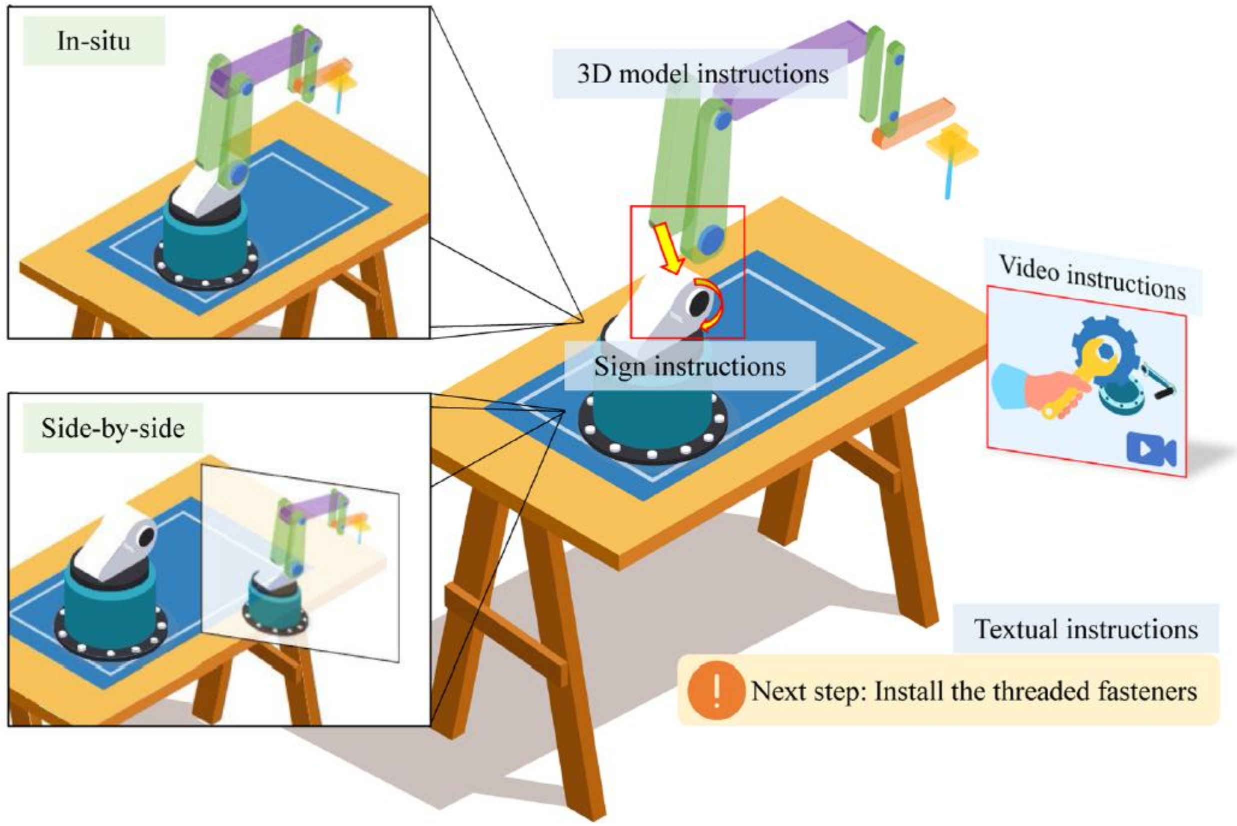

Fig. 4. Different visual instructions and presentation modes in CA-CAR assembly.

Figure 6: Image from W. Fang et al., 2025

4.3.2 Training and Knowledge Transfer

As shown in Figure 7, AR headsets such as the Apple Vision Pro can be used to walk through immersive training simulations with an expert remotely (*JigSpace for Apple Vision Pro - Bring Spatial Computing to Your Business.*, n.d.). This can benefit the onboarding of junior technicians in multinational enterprises as they can be matched with the right training modules and experts regardless of their location. While not a perfect substitute of course, it may reduce the need for hosting trainings in training centres and travel, for the same effect in workforce development. Furthermore, as AR headsets get used increasingly in the field and are filming / documenting during troubleshooting operations, these video logs may be stored in a central database that grows over time. This should add value on the long term as certain problems encountered in the field may be matched with known solutions from the past that have been filmed. Again, this may serve as a knowledge transfer tool where experts have solved certain problems in the past and juniors who encounter similar problems for the first time can learn from these videos as needed.

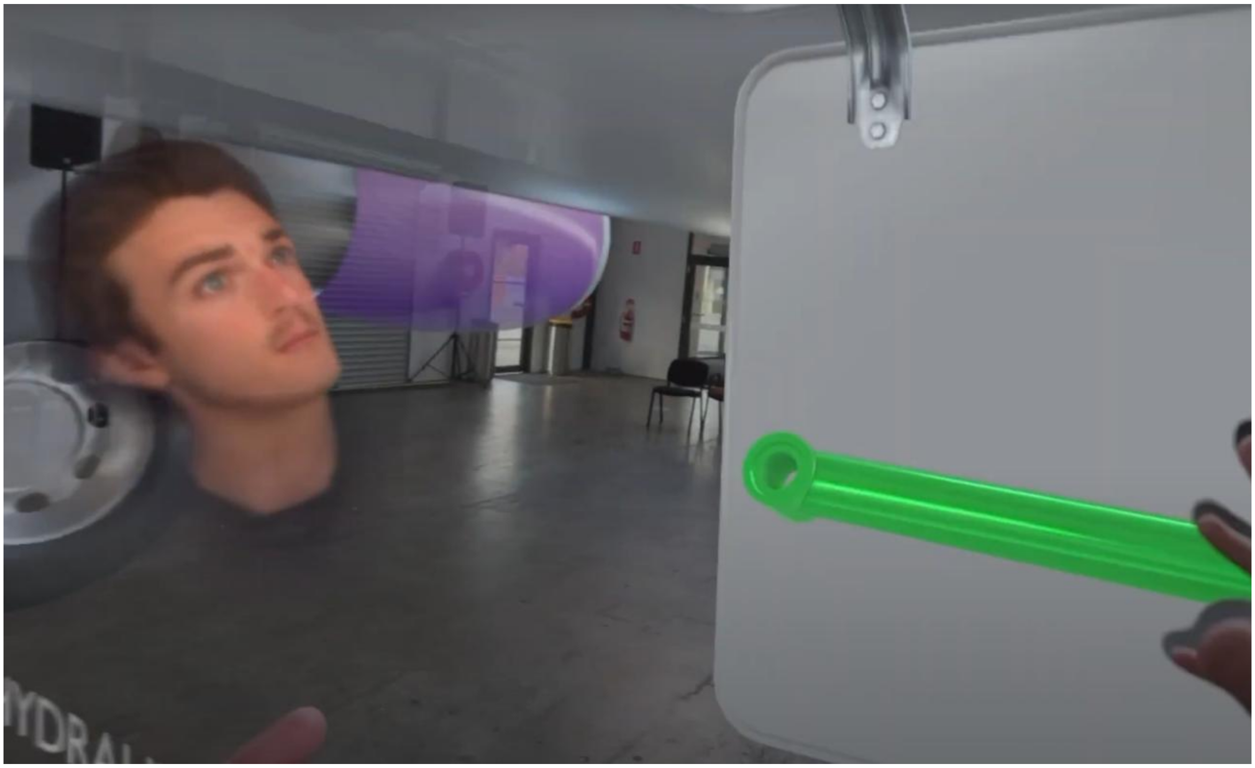

Figure 7: With the Jigspace application (a 3rd party application developed specifically for and with Apple Vision Pro's capabilities in mind), remote collaborative AR training on a multitude of industrial processes is possible, as long as the CAD models are there and the training modules are prepared, multiple remote persons can run through the training module together. The example shown here focusses on jet engine repair in a trainer-trainee fashion. Both persons can interact with the model and see the same manipulations, each other's avatars, and hands. It is as if they are working on a 3D model in the same room (JigSpace, n.d.).

4.3.3 Remote Expert Support

Experienced mechanics are becoming increasingly scarce (Appendix B), increasing the need for effective training, both through training modules as well as field experience through 'learning on the job'. Combining the benefits of both expert training, a video database and digital work instructions is the use case where live remote expert support is provided through the AR system. What better way is there than getting direct guidance from experts? AR also allows for more effective video calls with experts, who may give live annotations to guide the technician on specific problems in the field (Malta et al., 2023). The system can provide 'co-working' functionality on a specific digital work instruction a field technician may be struggling with, or if the real-world conditions are different from the module, the expert may guide the technician through the solutions that are not present in the work package. With the recording of the session, the video database can also be further expanded with a curated selection of clips from the remote support session, as and where needed. In essence, AR may support workforce development in the long-term due to several mechanisms.

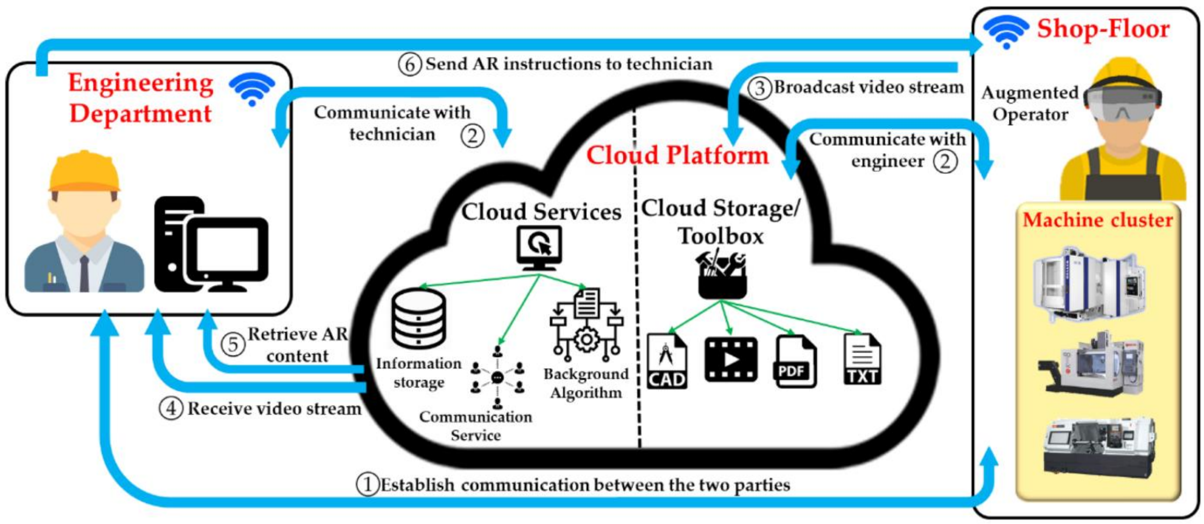

Figure 8: A proposed system architecture for remote expert support for AR enhanced field workers. This framework has been tested in real-life scenarios, validating that the functional requirements have been met (Mourtzis et al., 2020).

4.4 Barriers to Adoption

Despite its promise, AR adoption faces several challenges. Studies such as Behzadan et al. (2015) and Bottani & Vignali (2019) emphasize that many implementations remain confined to controlled environments, with limited transition to operational use. Pasquale et al. (2024) and Bottani & Vignali (2019) note that many AR systems are still perceived as experimental or "gimmicky," especially when not well integrated into existing workflows. Despite its potential, AR adoption in industrial contexts faces several persistent barriers:

- **Usability and Ergonomics**: Devices must be rugged, lightweight, and comfortable for extended use in harsh environments (i.e. offshore salt spray and heavy weather).
- **Integration with Legacy Systems**: Seamless integration with platforms like SAP is essential but often resource-intensive (see Appendix B). Companies may have limited capacity for IT infrastructure integration of new devices, so a business case needs to make keen sense. New systems (video database, AR tailored workflow and/or training catalogue) need to be created.
- **Privacy and Safety**: The use of video recording and real-time monitoring raises concerns among technicians, particularly in regulated or unionized environments. A limited field of view through the device might be dangerous (see appendix B).
- **Organizational Readiness**: As Ong et al. (2023) note, successful AR adoption requires not just technical feasibility but also cultural and procedural alignment. Change management needs to be carefully considered before implementation.
- **Uncertain effectiveness:** A 2023 scoping review by MDPI further emphasizes that while AR improves key performance indicators (KPIs) such as task time and error rate, its effectiveness is highly context-dependent and often limited by organizational inertia and lack of digital maturity.

These issues are especially relevant in offshore contexts, where environmental conditions and strict safety protocols further complicate deployment. Especially within Vattenfall, IT integration capacity is limited, requiring a strong business case for further implementation down the line (see Appendix A: 25-03-2025: First Visit Vattenfall, Interview with Person A).

4.5 Perception and Visibility Challenges

Another significant barrier to AR adoption in industrial contexts is the **perception gap** between consumer-facing AR applications and enterprise-grade solutions. Much of the public discourse and marketing surrounding AR is dominated by high-profile consumer use cases such as gaming, media consumption, and (office based) virtual collaboration and spatial computing (see Chapter 5, Figure 4 and Figure 13). These consumer-focused value propositions are promoted by major technology companies like Apple, Meta, Google and Samsung, while only one large technology company, Microsoft, created a product tailored to professional use cases (see Figure 16), the HoloLens, which is now discontinued.

These applications are often showcased in sleek product launches and viral campaigns, shaping public and stakeholder perceptions of AR as an entertainment tool. In contrast, industrial AR solutions designed for maintenance, training, and field service are typically marketed through niche B2B channels, trade shows, or technical white papers. As a result, key decision-makers in asset-intensive industries may be unaware of the maturity and specificity of AR tools tailored to their operational needs if they are not exposed to these channels. This disconnect can lead to scepticism about AR's practical value, especially when stakeholders are more familiar with consumer-grade devices than with rugged, enterprise-ready systems like RealWear (see Figure 17) or Microsoft HoloLens.

This perception gap is further reinforced by the lack of mainstream visibility for successful industrial AR implementations. While consumer AR experiences are widely shared on social media and tech blogs, industrial case studies may remain behind paywalls or within internal corporate reports, and public reports by AR service providers are obviously presented as biased marketing material (see Chapter 6). This asymmetry in exposure could hinder organizational buy-in, as stakeholders struggle to envision how AR can be effectively integrated into their workflows (Das & Narayan, 2025).

4.6 Offshore Wind Sector-Specific Relevance

While the majority of AR research and commercial development is focused on manufacturing and logistics (such as (Maio et al., 2023)), the offshore wind sector presents a uniquely compelling use case for AR technologies. Offshore wind operations involve complex, high-risk, and geographically dispersed maintenance tasks, often under time and weather constraints. These characteristics make the sector particularly well-suited for AR's strengths: applications that enhance remote collaboration, hands-free access to information, and enhanced training.

Moreover, the offshore wind sector is under increasing pressure to reduce the Levelized Cost of Energy (LCOE) and improve asset availability. AR can contribute to these goals by:

- Reducing the number of site revisits through remote expert support
- Enhancing technician training and onboarding
- Improving documentation and compliance through real-time video logging and digital workflows

Despite these advantages, the sector has seen limited large-scale AR deployments. This gap presents a valuable opportunity for exploratory research and pilot implementations, such as the one proposed in this thesis. By focusing on a real-world case at Vattenfall, this study contributes to filling the empirical gap in AR research within offshore wind and provides a roadmap for future adoption.

4.6.1 Empirical case study: Digital Assistance in Offshore Wind Maintenance

The study by Eggert et al. (2020) represents one of the few empirical investigations into digital assistance systems in offshore wind farm maintenance, in particular on railing crane maintenance workflows on the Arkona wind farm, a 385MW E.ON – Equinor site ("Arkona Offshore Wind Farm, Baltic Sea," 2020).

The research compares traditional paper-based workflows with digital workflows delivered via tablet devices and AR headsets, as shown in Figure 9: Empirical study into digitised maintenance processes on an offshore wind farm. Left: Tablet based workflow, right: AR glasses workflow (Eggert et al. (2020)).. While the study provides valuable insights into the operational feasibility of digital assistance systems in offshore contexts, the limited sample size (n=4) limits the generalisability of the findings. The study demonstrates that digital workflows, whether delivered via tablets or AR, can support maintenance operations by reducing media disruptions and improving information accessibility.

Figure 9: Empirical study into digitised maintenance processes on an offshore wind farm. Left: Tablet based workflow, right: AR glasses workflow (Eggert et al. (2020)).

Furthermore, while Augmented Reality (AR) was included as a delivery mechanism, the study's primary focus was on the broader concept of **digitalisation of information flows** in maintenance processes. The research examined how digital work instructions and logging systems could improve task execution and documentation. AR and tablets were evaluated as vectors for delivering these digital workflows, rather than a deep evaluation of the performance of these technologies.

The AR system was used to present digital checklists and collect inspection data, with hands-free interaction enabling technicians to maintain physical safety while operating in constrained environments such as crane rail areas being noted as a key advantage. This hands-free functionality of AR was noted as particularly beneficial. However, its industrial applicability was limited by the hardware constraints of the time (Eggert et al., 2020). Given the rapid pace of technological development in AR systems since

2020, it is plausible that many of these limitations have since been addressed, warranting renewed empirical investigation under current operational conditions.

The (n=4) technicians were ***"more convinced of the configuration of the assistance system on industry-standard tablet devices than a comparable range of functions on mixed reality glasses",*** which the researchers attribute to unfamiliarity and the lack of industrial applicability of AR glasses. AR headsets were perceived as less intuitive, with limitations in document display and searchability. These findings suggest that **user familiarity, interface design and technical capability** are critical factors in technology adoption.

The study mentions no prior training of technicians on the usage of these AR systems. This highlights the importance of training and onboarding, as unfamiliarity with AR systems may hinder adoption despite their potential benefits. These results align with broader literature indicating that successful AR adoption depends not only on technical capability but also on contextual fit, user-centred design, and organisational readiness (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025). The study further represents the need for further empirical research with larger sample sizes and more diverse operational scenarios to validate AR's effectiveness in OWF O&M.

4.7 Conclusion

In conclusion, **the literature strongly supports the null hypothesis** that Augmented Reality (AR) can deliver tangible benefits in industrial maintenance contexts, including improved efficiency, reduced error rates, and enhanced training. These benefits are particularly relevant to offshore wind operations, where logistical complexity, safety requirements, and cost pressures create a convincing case for digital augmentation of O&M workflows.

While AR offers compelling benefits, its success depends on:

- **Organizational Readiness**: Willingness to adapt workflows and invest in training.
- **Technical Fit**: Compatibility with existing IT infrastructure and safety protocols.
- **User Acceptance**: Ensuring that AR tools are intuitive, non-intrusive, and genuinely helpful.

Barriers such as user acceptance, integration challenges, and organizational readiness must be addressed through thoughtful implementation strategies and stakeholder engagement. By generating a business case for AR in OWF O&M, these barriers may be challenged or validated and perhaps even solved in subsequent studies.

The technology seems ready to emerge from theory, but the review also reveals a significant gap between AR's **technical maturity** and its **real-world adoption**, especially in offshore environments, which clearly manifests in the lack of (quality) empirical studies. This highlights the need for exploratory, context-specific research.

This thesis aims to address that gap by assessing the technical feasibility, organizational fit, and business value of AR in the context of Vattenfall's OWF O&M operations, providing the first steps on a path towards a potential empirical study in the form of a pilot.

5 State-of-the-AR: Capabilities and Market Landscape

In this chapter, a capabilities overview of state-of-the-art AR systems will be given. A literature review, highlighting the consensus in the scientific field, together with market research, shows the past developments, future direction, expected value adding capabilities and the realistically achieved usefulness of AR systems. Concludingly, this should show what the state-of-the-art is in this field and what use cases can be realistically augmented with the currently available systems, as well as highlighting which type of AR system to opt for in certain situations. Any current shortcomings and the future direction of AR systems may also be indicated in the scientific literature, giving perspective on use cases which may not be achievable today.

5.1 Established Use Cases for State-of-the-Art Augmented Reality

To understand the current capabilities and potential of AR systems, this section explores a range of high-performance applications across industries. Since the early concept of a head-mounted display for aircraft maintenance (Caudell & Mizell, 1992), AR has evolved into a versatile tool used in fields as diverse as aerospace, medicine, manufacturing, and education (Malta et al., 2023).

AR's potential is perhaps most evident in high-stakes environments where real-time decision-making is critical. In such contexts, AR functions as a **decision support tool**, delivering real-time, context-aware information directly into the user's field of view to reduce cognitive load and enhance situational awareness. A few high-performance use cases of AR are shown here to demonstrate the technology's capability range.

5.1.1 The F-35 Fighter Jet Helmet: AR as a Decision Support System

A compelling example of this is the **F-35 fighter jet helmet**, shown in Figure 10, which is one of the most advanced AR systems in operational use today. In combat aviation, pilots must make life-or-death decisions within fractions of a second. Introduced in 2015 (maiden flight in 2006), this fifth-generation fighter jet is a quantum leap above the fourth-generation F-16 (introduced in 1978). Traditional cockpit instrumentation, as seen in the F-16, requires pilots to divert their gaze from the external environment to read gauges and displays, an action that can be dangerous during high-G manoeuvres or in hostile scenarios.

Figure 10: F-35 pilot wearing a custom-fit helmet, which has integrated AR capabilities for flight information, 360-degree visibility and sensor integration, demonstrating AR's usefulness in a high-profile use case (Schradin, 2022).

The F-35 helmet overcomes this limitation by integrating AR directly into the pilot's line of sight. This $400,000 custom-fit helmet provides a continuous stream of mission-critical data, sourced from multiple onboard sensors and external systems, projected onto the helmet's visor, shown in Figure 11. Key capabilities include (*JHMCS II Helmet Mounted Display | Elbit Systems*, n.d.):

- **Heads-Up Display (HUD)** elements showing avionics, flight data, and mission parameters at all times.
- **360-degree situational awareness** via (normal and infrared) cameras mounted around the aircraft, allowing pilots to "see through" the plane.
- **Real-time overlays** of:
    - Terrain and topography.
    - Sensor feeds (e.g., Laser Designator Pod video).
    - Threat detection and blue-force tracking.
    - Weapon systems status and targeting information.
- **Enhanced radar and defence system integration**, displaying enemy and friendly aircraft positions.

This system transforms the pilot's helmet into a fully immersive command interface, enabling faster reaction times, improved targeting accuracy, and reduced mental workload. Unlike legacy systems, where pilots must mentally synthesize data from multiple instruments, the F-35 helmet presents a unified, intuitive visual stream, keeping the pilot's attention focused outward.

Figure 11: In-helmet HUD avionics and see-through plane night vision as displayed to the pilot (Joint Strike Fighter F-35 | Helmet Mounted Display System, n.d.).

With over 400,000 flight hours logged and more than 2,000 helmets deployed as of mid-2022, the F-35 helmet is a proven AR solution in one of the most rugged, mission-critical environments. Its success underscores the potential of AR to enhance human performance in other complex domains, including offshore maintenance, emergency response, and remote medical procedures.

5.1.2 Telesurgery and Remote Medical Collaboration

Figure 12: Telesurgery on an animal, spanning a 1200km distance in China, enabled by high-speed, low-latency (5G and fibre optic) networks. A surgeon console with operating room and control room views allows a doctor to remote control a surgical robot (Patel et al., 2024).

The **Lindbergh operation** in 2001 was the first successful telesurgery, which marked a pivotal moment in the evolution of remote medical procedures (Marescaux et al., 2002, Hidaya Aliouche, 2021). Performed across the Atlantic using robotic systems, it demonstrated that surgical expertise could be delivered globally, in real time, without the physical presence of the surgeon. Since then, telesurgery has undergone continuous innovation, with **Augmented Reality (AR)** and **Mixed Reality (MR)** technologies playing an increasingly key role in research for enhancing precision, communication, and accessibility (Patel et al., 2024).

Modern telesurgical systems integrate the following (Rocco et al., 2024):

- **Robotic surgical platforms** such as the Da Vinci 5.
- **High-resolution 3D displays** and **haptic feedback devices** (e.g., cybergloves).
- **Ultra-low latency communication networks** (e.g., 5G, fibre optics).
- **AR overlays** for anatomical guidance, procedural steps, and real-time remote collaboration.

These technologies allow expert surgeons to operate on patients located thousands of kilometres away, significantly reducing the need for travel and expanding access to high-quality care in underserved or remote regions, including rural hospitals, disaster zones, and military outposts. As can be seen from Figure 12, these systems do not currently use HMD's but rather use large consoles as the surgeon does not require a portable system in this case. The functionality is however the same, and it is expected HMD's will be applied more in the future to provide more screen real estate and immersion (Patel et al., 2024).

Several platforms and institutions have reported successful telesurgical trials and deployments (Rocco et al., 2024):

- **Hinotori (Japan)**: Robotic-assisted platform tested in pre-clinical remote surgery scenarios.
- **Edge Medical (China)**: Over 100 animal and 30 human surgeries performed remotely.
- **KanGuo (China)**: Human telesurgeries conducted over distances exceeding 3000km.
- **Microport (China)**: More than 100 human operations completed at distances up to 5000km.

These examples highlight the feasibility of long-distance surgery, though challenges remain in areas such as **cybersecurity**, **data privacy**, **technical reliability**, and **regulatory compliance**.

5.2 Consumer and Enterprise Grade AR Systems

Since 2015, the development of Augmented Reality (AR) has shifted from niche industrial applications to mass-market consumer and enterprise solutions. Major technology companies, including Apple, Microsoft, Meta, Google, and Samsung, have invested heavily in AR platforms. This has accelerated the development of high-fidelity, wearable AR and Mixed Reality (MR) systems, aiming to integrate users and developers into their (broader) hardware and software ecosystems.

The convergence of spatial computing, intuitive user interfaces, and high-performance hardware has enabled AR systems to transition from experimental tools to operational assets. These platforms serve not only entertainment and productivity purposes but also act as development environments for third-party applications in fields such as healthcare, education, and industrial maintenance.

The AR platforms serve as **multi-sided platforms,** similar to the business model of game consoles, where the users benefit from massive R&D developments into the ecosystem and its applications, while application developers potentially reach a large customer base that are seeking the specific application features only supported by the AR systems/units.

Naturally, the AR platforms will only succeed in reimbursing the development and AR systems unit costs if the user base grows large enough. The AR systems may even be sold as a loss leader, enticing more users into the AR platform. However, taking one step back, the AR platforms itself may be viewed as a loss leader for the larger ecosystems (Google, Apple, Microsoft, Meta). With an estimated Total Addressable Market (TAM) for wearable devices of 95B in 2025 (est. 2017), there is stiff competition among the large technology companies in innovation, pricing, and features (Stefan Hall & Ryo Takahashi, 2017, Soumyakanti, 2025).

5.2.1 The Cutting Edge: Apple Vision Pro

The **Apple Vision Pro** (see Figure 1) represents the cutting edge of consumer-grade AR/MR technology in a fully integrated hardware-software ecosystem. It combines ultra-high-resolution, full FOV passthrough AR with advanced spatial computing capabilities, including gesture, eye, and voice control, as well as support for inputs like spatial VR controllers, pens, and traditional keyboards and mice. The device can be used standalone, but is also deeply integrated into Apple's broader ecosystem, enabling seamless interaction with iPhones, iPads, and Mac devices.

With a steep price of $3500, the product attracts primarily a niche market of enthusiast and professionals. The device is increasingly seen as a **development platform** for futuristic capabilities that third-party developers are rapidly building upon, increasing its perceived value over time.

Although technically a VR headset with high-fidelity video passthrough rather than a true optical see-through AR device, the Vision Pro delivers a convincing and immersive AR experience. Its real-time responsiveness, intuitive interface, and spatial awareness make it suitable for a wide range of office-based workflows. It functions as a large, immersive workspace overlaid on top of the room you're working in (AR mode, see Figure 13), but a fully virtual room can also be used as the background (VR mode).

Figure 13: Apple Vision Pro user experience in "2D" AR mode: You can use it as a very high definition (12 MP per eye (4K = 8MP)), ultra-wide monitor to enhance your work space where screen real estate is projected over your entire field of view, while still showing the real environment. Works standalone or enhances phone / laptop workspace. This is one of the more 'traditional' workflows offered by the system, enhancing the user experience people are already accustomed to (i.e. computing on a large screen) (Apple Vision Pro, n.d.).

Although offering some benefits over a TV, PC, laptop, or smartphone towards consumers, its $3500 price tag may be considered prohibitive when used purely as a luxury media consumption or gaming device (though gaming is an excellent capability demonstration of the integrated systems, see Figure 4). This may attract a niche market, but the product's applications are mainly aimed towards office, creative and knowledge workers. The shared spatial computing system can import the lifelike 3D personas of co-workers into your workspace and vice-versa (*visionOS 26 Introduces Powerful New Spatial Experiences for Apple Vision Pro*, n.d.). Use cases include remote expert support, immersive training simulations (see Figure 7), (CAD) design reviews and team meetings. These remote collaboration features reduce the need for travel and physical tools (monitors / projectors / conference rooms) and may accelerate workflows (Egger et al., 2023), (O'Callaghan, 2024).

The Vision Pro is <u>not built for harsh environments like offshore wind farms,</u> but its capabilities make it a strong candidate for **enterprise users.** Its ability to act as a large, immersive, full-field-of-view workspace makes it particularly attractive for enterprise use cases where screen real estate, multitasking, and contextual awareness are critical (see Figure 13). The portability of the device means that high-performance spatial computing can be performed at almost any location away from the (home) office. This can provide a high-value productivity increase for travelling businesspeople for example, as travel days are generally considered a waste in cases where a laptop may be too bulky or does not provide enough screen real estate for the specific computing tasks efficiently.

5.2.2 Mass Market Focus: Meta Glasses / Meta Quest 3

Meta has focused on consumer AR experiences, particularly in social media, entertainment, and gaming contexts. The Meta Ray Ban AI glasses offer a purely camera / voice-based experience without any display, **disqualifying it as an AR system.** However, it may be useful for one-way video calls/recording or voice prompts with audio cues from the AI system if used in an enterprise setting (*AI glasses Designer Eyewear for Effortless Connection*, n.d.). The Quest 3S offers almost the same consumer-focused features as the Apple Vision Pro at 1/10th of the unit cost but focuses solely on media consumption and gaming (*Meta Quest 3 | Ultimate Power Meets Premium Comfort*, n.d.).

Figure 14: The Meta Quest 3 MR device including controllers can be used for media consumption, gaming, and social media (Meta Quest 3 | Ultimate Power Meets Premium Comfort, n.d.).

Both systems are **not aimed at enterprise or industrial use at all,** as no integration with enterprise systems are offered and there seem to be no third-party developments for enterprise applications. However, Meta's R&D in AR continues to influence the broader market and making AR technology more accessible due to the low price. Therefore, the system is still mentioned in this research, as future iterations may expand into enterprise use cases as the technology and market matures.

5.2.3 Soon to be launched: Android XR (Samsung XR)

Samsung, in collaboration with Google and Qualcomm, is developing a suite of AR products under the **Android XR** umbrella, which should launch before the end of 2025 (*Unlock the Infinite Possibilities of XR With Galaxy AI*, 2024). These range from full-featured mixed reality headsets to lightweight smart glasses. Compared to Apple's closed ecosystem, Android XR offers similar technical capabilities with a more flexible open ecosystem, but the user experience may vary across devices and lack the same level of integration and polish (Florence Ion, 2025). The software is mainly tailored towards mass-market consumers, using AI integration and voice inputs to provide digital contextual prompts of the surrounding environment, the platform's openness to other hardware and software may prove advantageous in industrial settings where ruggedness, features, modularity, application availability and IT integration are critical.

Figure 15: Samsung XR device "project Moohan" (Unlock the Infinite Possibilities of XR With Galaxy AI, 2024).

5.2.3.1 Continuation of (failed) Google Glass

Samsung's XR device seems to be better equipped for market success than the 2014-2015 Google Glass product (Florence Ion, 2025, Justin Burton Weidner et al., 2024, Reynolds, 2015). With limited AR functionality, a difficult user experience, immature hardware not fit for purpose, (bystander) privacy concerns, and a luxury price tag of $1500, Google failed to create a market niche, and the product quickly failed. A marketing failure the product also contributed to the product's demise. People were unsure why, how, and when to buy the product, as the value proposition, customer relations channels and customer sales channels were unclear.

5.2.4 Product failure: Microsoft HoloLens

As one of the first consumer and enterprise grade VR products backed by a trillion-dollar market cap technology company, the Microsoft HoloLens 1 and 2 products are an important case to review. Obvious signs of early mover disadvantage are shown, where a **technologically immature** but otherwise well thought out product eventually **failed.**

Figure 16: The Microsoft HoloLens 2 was specifically aimed at enterprise and industrial use, featuring some ruggedness such as IP50 dust-proof rating, hardhat compatibility and operability with gloves (Jowita Kessler, 2022).

With the HoloLens 1 released in 2016, and the HoloLens 2 released in 2019, Microsoft became the first large technology company to bring an AR device to the mass market that was specifically tailored for and heavily marketed towards enterprise users. The HoloLens' hands-free operation, spatial mapping, and integration with enterprise systems such as Microsoft Teams and Dynamics 365 made it ideal for industrial processes such as remote expert support, digital work instructions and training. However, these features did not weigh up against the **technical immaturity:** a small FOV, poor image quality, flickering, and hard to read text led to reported eye strain from users. This led to disappointing enterprise uptake, as companies found the device difficult to use and integrate into existing workflows.

Weak sales, intense competition, and talent drain from the development team has eventually led to Microsoft discontinuing the product in October 2024 with no successor announced, ending product support in December 2027 (Mark Hachman, 2024).

Once a pioneering product line in enterprise AR, its disappointing hardware features, user discomfort, limited adoption, prohibitive cost, and lack of sustained platform support ultimately led to its demise (Rob Starks Jr, 2022). For companies like Vattenfall considering AR solutions, this underscores the importance of choosing platforms with long-term vendor commitment and ecosystem support.

5.3 Conclusion and Relevance to OWF O&M

It is important to consider the requirements for an AR system when it serves to enhance a certain business process. For example, even though the Apple Vision Pro seems to offer the most comprehensive suite of AR / MR / VR hardware and software functionality, attracting a growing user and developer base and thus ensuring long term product support, this still represents a compromised design for the use case of OWF O&M, **as the device is not rugged enough for this application.**

Invertedly, more niche AR systems are available that may provide a perfect match for the requirements. This advantage is simultaneously a risk, since a lack of adoption and uncertain future product support **may hurt the long-term usefulness for customers.**

With AR's scientific field (see Chapter 4) and capabilities now mapped, it is evident that AR systems are, in principle, capable of enhancing industrial processes. However, a critical observation emerges: the major technology platforms currently driving the most prominent AR development, such as Apple, Meta, and Google, are primarily focused on consumer and enterprise applications. As deducted from the analysis presented in this chapter and corroborated by the findings of Eggert et al. (2020), these consumer-based systems, while technically advanced, often lack the ruggedisation, integration capability, and ease of use required for deployment in industrial environments such as offshore wind farm maintenance. Furthermore, Microsoft's HoloLens, which was one of the few AR platforms explicitly targeted at industrial use cases, failed to gain sufficient market traction due to technical immaturity and a difficult user experience, and has since been discontinued. This misalignment between technological innovation and industrial applicability requirements underscores the necessity for sector-specific solutions and empirical validation under operational conditions.

Notwithstanding these limitations, AR has demonstrated substantial value as a decision support system in high-stakes environments. Notable examples include its integration into the F-35 fighter pilot helmet and its emerging role in telesurgery applications. These precedents suggest that, with appropriately tailored solutions towards OWF O&M, AR can deliver significant operational benefits.

6 Market Analysis: AR enhanced Field Service Management systems

This chapter presents a targeted market analysis of AR enhanced Field Service Management (FSM) platforms, which are identified as a key entry point for AR integration into OWF O&M activities. FSM platforms serve as the digital backbone for coordinating field operations, and their existing integration with Enterprise Resource Planning (ERP) systems such as SAP, already deployed within Vattenfall, makes them a logical and potentially low-barrier pathway for introducing AR capabilities, further enhancing the performance of these digital FSM platforms (*What Is Field Service Management (FSM)?*, 2021 and *Field Service Management (FSM)*, n.d.).

Building upon the academic landscape and technological capabilities of AR systems outlined in Chapters 4 and 5, the objective is identifying commercially available FSM solutions that support AR functionality, evaluating their technical and functional maturity for OWF O&M, and exploring their compatibility with Vattenfall's digital infrastructure and operational environment.

These guiding questions structure this analysis:

- Why is FSM a suitable entry point for AR into OWF O&M?
- What AR-enhanced FSM solutions are currently available that could improve Vattenfall's OWF O&M workflows?
- Has the commercial market caught up to the current technological capabilities of advanced AR systems and the operational requirements of customers in this specific field?
- How do the solutions compare to each other, and which one would be the most appropriate candidate for further implementation within Vattenfall?

6.1 Field Service Management: Definition and Relevance

Field Service Management (FSM) refers to the coordination and execution of field-based operations through digital platforms that manage scheduling, dispatching, task execution, and reporting. These tasks typically include installation, maintenance, inspection, and repair of equipment or infrastructure at remote or customer sites (see *What Is Field Service Management (FSM)?* 2021 and *Field Service Management (FSM)*, n.d.).

FSM encompasses several core components:

- **Scheduling and Dispatching**: Assigning technicians to tasks based on availability, skillset, and location.
- **Work Order Management**: Tracking service requests from initiation to completion.
- **Inventory and Asset Tracking**: Managing tools, spare parts, and consumables required for field operations.
- **Mobile Workforce Enablement**: Providing technicians with mobile access to documentation, diagnostics, and communication tools.
- **Contract and SLA Management**: Ensuring service delivery aligns with contractual obligations and performance standards. This is more applicable to third party service providers, but internal teams within Vattenfall can use this to ensure compliance with internal standards.

6.1.1 FSM in Asset-Intensive Industries

The offshore wind sector presents a challenging operational environment, characterised by remote locations, harsh weather conditions, and high safety standards. These factors make maintenance operations difficult and expensive. Simultaneously, wind turbines produce high marginal profits once operational, meaning the cost of production loss is high and **asset availability is therefore priority number one.** These conditions are shared by a wide range of asset-intensive sectors such as manufacturing, transportation, (other renewable) energy and utilities, (civil) infrastructure and the oil and gas industry.

FSM platforms are tailored specifically towards usage in such asset-intensive industries. Accordingly, the scope of this market analysis is broadened to include FSM systems deployed in these analogous industries, thereby increasing the likelihood of identifying AR-integrated solutions which are applicable to OWF O&M.

6.1.2 FSM and ERP Integration

Enterprise Resource Planning (ERP) platforms manage core business functions including finance, procurement, and asset lifecycle management. FSM platforms typically integrate with ERP systems such as SAP, enabling seamless data exchange across operational, logistical, and financial domains. Within Vattenfall, SAP is already deployed, using rugged tablets, for work order management, documentation, and resource planning (see Chapter 7 and Appendix B). **This makes FSM a natural integration point for AR-enhanced capabilities.**

6.2 Scope and Limitations of the market analysis

This market analysis complements the literature review in Chapter 4, which outlines the theoretical benefits of AR in industrial maintenance, and the capability overview in Chapter 5, which demonstrates AR's capability range and operational value in adjacent sectors. By surveying the current state of commercially available, tailor-made FSM platforms that support AR headsets, this chapter provides a practical foundation for assessing integration feasibility and identifying candidate systems for pilot implementation. **The focus remains on identifying enabling technologies rather than prescribing a definitive solution.**

6.2.1 Existing Tablet-based SAP Workflows

Since Vattenfall already employs SAP-integrated tablets for field operations, a natural question arises: does Augmented Reality (AR) offer a superior alternative to existing tablet-based FSM systems? **This market research does not aim to evaluate AR as a replacement for tablets,** nor does it compare the two modalities directly. Rather, the focus is on identifying how AR systems can be employed within existing FSM or ERP platforms to complement and enhance specific workflows through AR's unique capabilities, such as hands-free operation, contextual visualisation in the operator's Field of View (FOV), and remote expert collaboration, as outlined in Chapters 4 and 5.

These workflows are already embedded in Vattenfall's operational infrastructure via SAP, and AR integration through market-ready FSM platforms may offer a more feasible and scalable pathway for deployment than attempting to replace current systems outright. The emphasis is therefore on complementarity and enhancement, not substitution.

6.2.2 Limitations of using marketing material

This chapter critically evaluates the current market offerings, with particular emphasis on their real-world applicability in OWF O&M, limitations, and operational impact. **Given the scarcity of independent case studies in literature (see Chapter 4), the analysis necessarily draws upon vendor documentation and marketing material.** This material is treated with appropriate scepticism, and the researcher has taken care to triangulate claims with available literature and stakeholder insights. Nevertheless, market research remains a valuable complement to academic inquiry, particularly in emerging technological domains where empirical studies may lag behind commercial development, as is indeed the case for this topic.

6.2.3 Not a full-depth market evaluation

As this thesis adopts a design-oriented research approach (see Chapter 2 and 3), the market analysis presented in this chapter is intentionally scoped as a high-level overview of available AR-enhanced FSM solutions. The aim is not to determine which solution is definitively best for Vattenfall at this stage. Instead, the analysis aims to map the current landscape of industrial FSM platforms that support AR integration, highlighting their core functionalities, deployment maturity, and potential compatibility with existing digital infrastructure. Particularly the ease of integration with SAP is investigated and highlighted where possible, which is already in use at Vattenfall and has been identified as a key barrier to entry due to limited Digital Engineering resources (see Chapter 7).

6.3 Evaluation Criteria

To assess the suitability of AR-enhanced FSM platforms for OWF O&M, five evaluation criteria have been defined. These criteria are based on the research outline (Chapter 3) and derived from the literature synthesis (Chapter 4), the technological landscape review (Chapter 5), and the operational requirements identified in stakeholder interviews (Chapter 7). Each criterion reflects a critical aspect of deployment feasibility in offshore environments:

- **Technical Fit**: Offshore wind farms operate in harsh conditions: salt spray, high humidity, high winds, and temperature fluctuations. Devices must be ruggedised to withstand these environments and being knocked around, support hands-free operation for safety and efficiency, and maintain usability while technicians wear personal protective equipment (PPE).
- **Functional Fit**: AR systems must support key functionalities such as remote expert collaboration, digital work instructions, and immersive training.
- **Integration Capability**: Seamless integration with existing ERP systems (such as SAP) is essential for workflow continuity, documentation, and compliance. Vattenfall's current use of SAP for work order management and reporting necessitates that any AR solution be interoperable with this infrastructure, as noted in Chapter 7 and Appendix B.
- **Deployment Maturity**: Given the limited internal capacity for custom development, preference is given to solutions with proven deployments in energy, offshore, or similarly demanding industrial sectors. This reduces implementation risk and increases the likelihood of successful adoption.

6.4 FSM Platform Market Overview

To identify suitable AR-enhanced FSM platforms, a structured market scan was conducted using general search queries in Google and vendor documentation. Further analysis was performed using a targeted prompt engineering queries in M365 Copilot (A Large Language Model Artificial Intelligence tool, see Chapter 3 and 12) after the initial search to expand the scope and find other market offerings which may have been left out in the initial internet search.

The results include both hardware and software offerings, with a focus on solutions that have demonstrated applicability in industrial or offshore contexts. A comparative evaluation table is presented below to summarise the findings. This table provides a side-by-side assessment of each solution against the five evaluation criteria introduced above. It serves as a decision-support tool for identifying the most promising candidates for pilot implementation.

The general internet search was performed using prompt logic:

- (“Augmented Reality” OR “Field Service Management”) AND (“Operations and Maintenance” OR “O&M”)
- (“Augmented Reality” OR “Field Service Management”) AND (“Operations and Maintenance” OR “O&M”) AND (“Offshore Wind Farms” OR “Offshore Wind” OR “OWF” OR “Industrial” OR “Oil and Gas” OR “energy”)

The initial results were refined and enhanced using an AI LLM tool. Reviewing the results, mainly the company websites and vendor documentation, identified several AR-enhanced FSM platforms which may be suitable for integration with OWF O&M.

6.5 FSM System Analysis

The identified platforms are expanded here. Their functionalities are explained in the context of OWF O&M and suitability for integration of AR enhanced workflows within Vattenfall:

6.5.1 RealWear – Navigator 520 / Z1

RealWear’s Navigator 520 and Z1 smart glasses are purpose-built for industrial environments, offering a rugged, hands-free solution that integrates seamlessly with enterprise platforms such as Microsoft Teams and Azure (*RealWear Navigator 520 | Devices*, n.d.). The devices are ***exclusively* voice-controlled,** enabling full hands-free operation. Furthermore, they are compatible with personal protective equipment (PPE), making them particularly suitable for field service and offshore applications (see Figure 17). Additionally, the inclusion of thermal imaging and high-resolution cameras enhances their utility for diagnostics and remote collaboration.

However, the exclusive reliance on voice commands introduces significant usability constraints, particularly in noisy or multilingual environments. In sectors such as the Northwestern European offshore industry, technicians often operate in high-noise conditions and speak with diverse non-native English accents. The voice-only interface may then impede efficient navigation of digital workflows, such as accessing file directories or completing structured forms. Furthermore, the system depends on third-party software for a full AR functionality suite.

While the hardware is demonstrably robust and fit for purpose, its operational effectiveness is ultimately contingent upon the reliability and intuitiveness of its voice recognition system as well as software integration. This limitation raises concerns regarding user adoption and task efficiency in real-world deployments, where precision and speed are critical.

Figure 17: Realwear uses a relatively simple display technology that does not fully block the user's FOV, ensuring normal peripheral vision and safety (RealWear Navigator 520 | Devices, n.d.).

6.5.2 OverIT – NextGen FSM

OverIT's NextGen FSM platform is a technologically mature Field Service Management solution that integrates AR capabilities with Enterprise Resource Planning (ERP) systems, including SAP. Its deep SAP integration enables seamless synchronisation of work orders, service instructions, and reporting workflows, thereby reducing manual data entry, and improving compliance with existing digital infrastructure.

Delivered via a Software as a Service (SaaS) model, the platform supports a wide range of AR hardware, including ruggedised headsets such as RealWear. Key functionalities include hands-free remote expert collaboration, offline-accessible digital work instructions, and content sharing tailored to field technicians. These features are designed to enhance operational efficiency and reduce the need for on-site expert deployment. Additionally, the platform incorporates a machine learning-enhanced database that facilitates the extraction, cataloguing, and reuse of recorded sessions, enabling expert technicians to generate customised work instructions and troubleshooting guides.

*Figure 18: OverIT's FSM Platform allows both tablet and AR based workflows, training and remote collaboration and is compatible with multiple AR headsets, including those compatible with hard hats such as **RealWear** (shown here) ("NextGen FSM - Field Service Management Software Product," n.d.).*

The company operates for over 25 years in industrial environments with over 200 customers. Notable deployments include (*Customer Success Stories*, n.d.):

- Wind turbine maintenance at **EnBW**, where AR-enabled training workflows are expected to reduce training effort by 50% and improved first-time fix rates by 45%. The voice-actuated AR system from RealWear is used for field recordings performed by expert technicians. Videos, documents, pictures, diagrams, and digital work instructions associated with service orders (from SAP) are provided to field technicians (on a device of choice). Field technicians can connect with experts for remote guidance ("EnBW - Training on-the-Job for Maintenance on Wind Turbines," n.d.).
- At **Enel**, an Italian multinational utility operating in Brazil, expected 52% increase in productivity is predicted through remote supervision of quality checks on over 700 sites that should avoid approximately 950 annual travels of expert personnel, increasing availability by 1980 person/days per year. This direct guidance by remote experts simultaneously supports the training of the AR enhanced field technicians ("Enel - Virtual Quality Checks," n.d.).

The platform's strengths lie in its deep ERP (SAP) integration and its capacity to deliver real-time, hands-free support via AR annotations, video recordings, and offline-accessible digital procedures in a virtual repository. Furthermore, OverIT's proven track record and interoperability with third-party systems position it as a robust candidate for structured operations and maintenance (O&M) workflows.

6.5.3 Librestream – Onsight Platform

Librestream's Onsight FSM platform combines AR, AI, and IoT for remote inspections and knowledge capture. It supports low-bandwidth operation and has been deployed in manufacturing and inspection use cases in the food, aerospace, and defence sectors ("Digital Work Instructions," n.d.). The platform seems to offer similar capability as OverIT but seems to have more focus on handheld devices and less integration with wearable AR devices. Furthermore, there are less proven applications in the offshore and energy sector. SAP integration is also not mentioned on the company website.

*Figure 19: LibreStream's FSM platform integrates O&M workflows and remote assistance on PC's, tablets and wearables, including the **RealWear** headset shown on the bottom left ("Digital Work Instructions," n.d.).*

6.5.4 Kognitiv Spark – RemoteSpark

RemoteSpark is a software platform that focuses solely on AR remote collaboration with Azure integration and holographic annotations. Based on the videos from the company website, it seems to be using the Microsoft HoloLens 2 headset, demonstrating successful remote support sessions, where OEM's support customer technicians in troubleshooting (*Industrial-Grade Connected Worker Support: Real-Time Remote Guidance for Industrial Workers*, n.d.).

Figure 20: Kognitiv Spark remote expert support software combined with the Microsoft HoloLens 2 AR headset used in the field in a military setting (Industrial-Grade Connected Worker Support: Real-Time Remote Guidance for Industrial Workers, n.d.).

Its military-grade security is a differentiator, but its limited commercial adoption and hardware dependency (HoloLens 2 and proprietary RemoteSpark device) reduce its flexibility, especially given that the HoloLens platform has been discontinued, which raises issues for future reliability of the platform. However, with military (field service) use cases, it does demonstrate the HoloLens 2's suitability for rugged environments.

6.6 FSM Platform with AR integration capabilities

Only a handful of market offerings are seemingly available that integrate FSM software with AR headsets, which are summarised in the list below:

- **RealWear – Navigator 520 / Z1**: Rugged, voice-controlled smart glasses compatible with PPE. Strong hardware offering that is compatible with industrial use, but reliant on third-party software for full AR enhanced FSM functionality and SAP integration.
- **OverIT – NextGen FSM**: Offers deep ERP integration (including SAP), remote expert support, and digital work instructions. Deployed in many industries, including wind and energy sectors, with high productivity claims for over 25 years. Integrates with RealWear and SAP.
- **Librestream – Onsight Platform**: Combines AR, AI, and IoT for remote inspections. Supports low-bandwidth operation and multilingual environments. Seemingly offers the same functionality as OverIT, integrates with RealWear, but not with SAP, limiting its applicability within Vattenfall's existing digital infrastructure.

- **Kognitiv Spark – RemoteSpark**: Offers secure AR collaboration with Azure integration, primarily using Microsoft HoloLens 2 or proprietary AR headsets. Despite strong security features, the platform has limited commercial adoption and lacks documented ERP integration, making it less suitable for Vattenfall's operational context.

Although this does not constitute a comprehensive market review, the platforms examined here provide a representative overview of current AR-enhanced FSM capabilities. Consistent with the literature review in Chapter 4, these platforms typically support the following industrial use cases:

- Digital work instructions
- Remote expert support
- Video recording and training

6.7 FSM Platform Comparison

RealWear provides robust AR hardware but depends on external FSM platforms such as **OverIT** or **Librestream** for software functionality and ERP integration. Among the platforms reviewed, **OverIT** offers the most comprehensive feature set, including full SAP integration and compatibility with the robust RealWear devices which are suitable for industrial environments. **Librestream**, while functionally similar, does not explicitly support SAP, which may pose integration challenges. **Kognitiv Spark**, reliant on discontinued hardware and lacking ERP compatibility, is the least suitable option for Vattenfall despite positive testimonials in remote AR enhanced support in industrial contexts.

6.7.1 Comparison Table

A comparative evaluation table of the four AR-enhanced FSM platforms using the five defined criteria is shown below. Each platform is scored from 1 (poor) to 5 (excellent) per category, with a final column summing the total score. Explanations for each score are provided below the table.

Platform	Technical Fit	Functional Fit	Integration	Maturity	Total Score
RealWear	5	2	3	2	12
OverIT	4	5	5	5	19
Librestream	4	5	2	4	15
Kognitiv Spark	3	3	1	3	10

Table 1: Comparative evaluation table of the four identified AR-enhanced FSM platforms.

6.7.2 Scoring Justification

RealWear – Navigator 520 / Z1

- **Technical Fit (5)**: Purpose-built for industrial use; ruggedised, voice-controlled, and compatible with PPE.
- **Functional Fit (2)**: Limited native functionality; relies on third-party software for AR features such as remote support and digital instructions. Voice-only may not work with thick accents from non-native English speakers in noisy environments raises functionality concerns.
- **Integration Capability (3)**: No direct ERP integration; dependent on external platforms (e.g., OverIT or Librestream), but this is readily available.

- **Deployment Maturity (2)**: Seems to offer suitable AR hardware for industrial applications but is still a relatively new product. How will it hold up during long-term use?

OverIT – NextGen FSM

- **Technical Fit (4)**: Software platform; relies on compatible hardware (e.g., RealWear) for field deployment.
- **Functional Fit (5)**: Comprehensive AR features including remote expert support, offline digital instructions, and training workflows.
- **Integration Capability (5)**: Deep integration with SAP and other ERP systems; aligns with Vattenfall's infrastructure.
- **Deployment Maturity (5)**: Over 25 years of industrial experience; deployed in energy and wind sectors with documented success.

Librestream – Onsight Platform

- **Technical Fit (4)**: Compatible with rugged AR hardware; supports low-bandwidth and multilingual environments.
- **Functional Fit (5)**: Offers AR, AI, and IoT capabilities; supports remote inspections and training.
- **Integration Capability (2)**: ERP integration (SAP) not explicitly documented; potential barrier for Vattenfall.
- **Deployment Maturity (4)**: Established presence in manufacturing and defence; less visibility in offshore wind, but still more than 20 years of experience.

Kognitiv Spark – RemoteSpark

- **Technical Fit (3)**: Uses HoloLens 2 and proprietary hardware; less suited to offshore rugged conditions.
- **Functional Fit (3)**: Strong remote collaboration features; limited breadth in FSM functionality.
- **Integration Capability (1)**: No documented ERP integration; not suitable for SAP-based workflows.
- **Deployment Maturity (3)**: Niche use in food, defence, and aerospace, but with good testimonials. Uses proven but discontinued HoloLens (which has user experience issues) and proprietary hardware which is both not ideal.

In summary, <u>**RealWear + OverIT**</u> emerges as the most viable FSM platform for AR deployment within Vattenfall's offshore wind operations, offering both technical maturity in the form of a well-established software and rugged hardware platform and organisational fit through SAP integration. RealWear offers robust, voice-controlled AR hardware designed for industrial use, while OverIT provides comprehensive FSM software platforms with a high degree of integration maturity and deployment experience. OverIT, in particular, demonstrates strong alignment with Vattenfall's existing SAP infrastructure and operational workflows, making it the most viable candidate for structured deployment.

6.8 Discussion and Conclusion

The commercial ecosystem for AR in FSM has matured to the extent that several platforms now offer field-ready solutions with potential applicability to OWF O&M. Whilst a large set FSM software platforms suitable for offshore environments were found during the initial internet search and AI expanded search, only a handful support AR headsets, while most remain limited to smartphone, tablet and PC usage and are therefore excluded from this analysis. A notable exclusion is SAP, which offers an FSM solution that is integrated into its wider ERP platform but lacks direct support for AR headsets. Furthermore, only a subset of these AR-enabled FSM platforms meets the stringent requirements posed by offshore environments, particularly in terms of the ruggedisation, integration capability, and operational fit at Vattenfall. Still, a promising solution is found in the RealWear headset combined with the OverIT's FSM platform.

Despite these promising findings, the analysis is constrained by a critical limitation: the reliance on vendor-supplied documentation and marketing materials. While these sources offer valuable insights into product capabilities, they are inherently biased and lack independent validation. This limitation is particularly salient given the empirical gap identified in Chapter 1, where peer-reviewed case studies on AR deployment in offshore wind contexts remain scarce. Beyond vendor-supplied marketing material, these are not found elsewhere. Consequently, the findings of this chapter should be interpreted as indicative rather than definitive, and further empirical validation of these systems' effectiveness through pilot studies is strongly recommended.

Going forward, this research will consider a RealWear system, supported by OverIT's FSM integration, as the most suitable configuration for a possible pilot implementation within Vattenfall. These insights directly inform the subsequent chapter, which presents the results of semi-structured interviews with Vattenfall stakeholders. Chapter 7 will evaluate organisational readiness, user acceptance, and process suitability, thereby narrowing the scope to specific workflows where AR can deliver measurable value.

7 Interviews with Vattenfall Stakeholders

The full interview notes are presented in *Appendices A through E*, with key findings summarised in this chapter. While the number of interviews (five) may appear limited, each was selected purposefully and provides rich insights from a wide range of roles. Interviewees were identified primarily through referrals, with each participant having relevant experience either with AR technologies or with operational processes potentially suitable for AR enhancement. This approach prioritised depth over breadth, as appropriate for a low TRL assessment. Nonetheless, it is acknowledged that five interviews may not fully capture the diversity of perspectives within Vattenfall. The interviews are therefore interpreted as indicative of Vattenfall stakeholder views rather than exhaustive and are used to complement findings from the literature review and market analysis, gaining a wider perspective on the applicability of AR within the organisational structure of Vattenfall.

7.1.1 Appendix A: 25-03-2025 – First Visit Vattenfall, Brainstorm with Person A

Objective:
Initial exploration of AR use cases in offshore wind O&M.

Summary:
This initial engagement with Vattenfall, specifically with Person A, served as a foundational brainstorming session to explore the feasibility and value proposition of AR in offshore wind farm maintenance. The discussion revealed that AR is most promising for ad-hoc corrective maintenance rather than routine tasks. Key strengths identified include hands-free operation, reduced cognitive load, and enhanced remote collaboration. The concept of Context-Aware Cognitive Augmented Reality (CACAR) was introduced as a high-potential solution for delivering real-time, context-sensitive work instructions.

A critical insight was the potential for AR to support knowledge capture through video logging, which could be post-processed to build a searchable database of troubleshooting procedures. The session also highlighted organisational constraints, particularly the lack of digital engineering capacity to integrate AR platforms such as OverIT. This gap underscores the need for a robust business case to justify resource allocation. The discussion concluded with the identification of high-value use cases, including remote expert support and the reduction of revisits through real-time diagnostics.

Key Insights:

- AR is most promising for ad-hoc corrective maintenance, not routine tasks.
- Potential benefits of **Context Aware Cognitive Augmented Reality (CACAR)** are discussed: step-by-step (video, 3D) work instructions, hands-free operation, reduced cognitive load, and remote expert support (reduces expert travel time, increases expert availability through the video calls, enhances training on the job for field technicians)
- AR could help build a knowledge base through video logging and post-processing.
- **OverIT** was previously considered for testing and seemed to deliver useful services.
- **OverIT** was not tested due to **<u>internal resource constraints for implementation.</u>**
- With ad-hoc troubleshooting in the field, several revisits may be needed to fix a problem.

- AR could reduce site revisits and improve first-time fix rates, especially in offshore contexts where downtime and operation costs are high. **This should be of very high added value if this works!**
- Identification of AR system requirements and barriers to entry are important.
- New interview lead: Person B works in first line technical support and would be a strong candidate for further inquiries.

Use Case Highlight:
AR for remote expert support and knowledge capture during turbine troubleshooting **(Tech Tickets Process)** could help prevent costly revisits and thereby add significant value. Creating a sound business as a deliverable of the thesis would be helpful as a communication tool with management for initiating further projects into AR implementation within Vattenfall's stage-gate innovation management governance (see Figure 3).

Benefits:
Recording of first encounters helps with:

- Higher immediate first-time fix rate, as video calls allow for faster solutions in the field
- Higher future first time fix rate, as knowledge base expands with video catalogue.
- Higher second time fix rate, as accuracy of information for tech tickets increases.

Costs:
- Implementation (digital engineering, training)
- SaaS + Hardware (OverIT or similar + AR hardware fleet)
- Operations (Backoffice support, real time expert support, video cataloguing)

7.1.2 Appendix B: 14-04-2025 – Interview with Person B

Role:
Offshore platform expert with mechanical background.

Summary:
Person B, an experienced offshore technician, provided operational insights into platform reliability and the practical constraints of offshore maintenance. The interview emphasised that while AR may offer marginal improvements in task efficiency, its impact is often constrained by external factors such as weather delays and safety protocols. Nonetheless, AR was recognised as a valuable tool for streamlining Approved Work Procedures (AWPs), enhancing access to service instructions, and facilitating photo/video logging.

The integration of AR with SAP was identified as a critical enabler, particularly for digital documentation and workflow compliance. The interview also raised concerns about the ergonomics and practicality of AR devices in offshore environments. While remote expert support via smart glasses was deemed non-essential in current practice, the potential for AR to centralise and distribute expert knowledge through structured video databases was acknowledged as a strategic opportunity.

Key Insights:

- Uptime maximisation is top priority for OFW O&M activities. Downtime is very costly due to production loss.
- AR can marginally improve task efficiency but is constrained by weather and safety protocols.
- Highest-value use case: virtual document storage integrated with SAP.
- AR could streamline Approved Work Procedures (AWPs) and reduce reporting time.
- Smart glasses could enhance access to service instructions and enable photo/video logging.
- Remote expert support is currently done via phone; AR could improve this but is not yet essential.
- Emphasis on building a usable knowledge database from field recordings.
- Operational realities (weather, site travel) often mean lots of downtime for mechanics.
- Maintenance operations are already heavily digitised: SAP integration on rugged tablets provide workflows, reporting, and documentation help.

Use Case Highlight:

- Digital AR Work Instructions to streamline AWPs.
- Photo / video logging during work procedures smooths reporting process, saves time, makes reports more accurate.
- Use the photos / videos to build distribute knowledge through trainings and increase knowledge for field technicians over time. Focus on building technician expertise through trainings rather than the knowledge base itself. Make sure the <u>knowledge is distributed,</u> not centralised.
- AR remote expert support not really interesting, calls through phone are good enough. Experts on site are better than having them remote.

Requirements:

- A compelling value proposition to ensure adoption by technicians.
- Privacy features (face blurring, pause recording button, clear indication when recording is on)

Barriers to entry:

- Privacy (Big Brother is Watching feeling, small PPE violation 'to get things done' reprimand fear)

7.1.3 Appendix C: 24-04-2025 – Interview with Person C

Role:

Platform Asset Manager with prior experience at TNO in robotics and AR/VR.

Summary:

Person C, a Platform Asset Manager with AR/VR experience, emphasised that AR has broad potential if safety and practicality are ensured. Based on prior work at TNO, he noted mixed system performance and stressed the need for clearly defined, context-specific use cases. Privacy and safety concerns were identified as key requirements and barriers in offshore environments.

Key Insights:

- AR has potential across many areas if implemented safely and practically.
- Mixed results from testing 8–9 AR/VR systems.

- Emphasised the importance of defining specific, safety-compliant use cases.
- Supported further exploration of AR applications in offshore wind.

Requirements:

- Ensure the AR system meets safety standards.
- Ensure the AR system does not distract the worker.

Barriers:

- Privacy (filmed at workplace)

7.1.4 Appendix D: 23-05-2025 – Interview with Person D and Person A

Focus:
Tech ticketing process and revisit frequency.

Summary:
This session focused on the tech ticketing workflow and the operational inefficiencies arising from revisit requirements. The interview revealed that **revisits may often be necessitated due to incomplete diagnostics during initial site visits,** leading to delayed problem resolution and increased costs. AR was proposed as a solution to enable real-time remote assistance, thereby reducing the need for multiple site visits.

The concept of an **AR-enabled remote support hotline** was introduced, allowing technical support engineers to assist field technicians **before formal ticket creation.** This proactive approach **could improve first-time fix rates** and reduce downtime. The interview also identified the need for researcher data access to quantify revisit frequency and assess the potential impact of AR. The discussion concluded with a recommendation to explore AR applications in and live expert collaboration, aiming for immediate problem solving, thereby preventing the creation of a ticket.

Key Insights:

- Tech tickets are often delayed due to lack of real-time communication: tickets are created after shifts and answers may take days / weeks.
- Revisit frequency may be high due to incomplete diagnostics during initial visits.
- Highlighted the need for data access to quantify revisit reduction potential.
- AR could enable real-time remote support, reducing unnecessary revisits.
- Suggested a remote support "hotline" using AR before tickets are formally logged, potentially solving problems before tickets need to be created.

Use Case Highlight:

1. AR could be used as a remote expert support hotline, where experts are on call during operations to ensure problems that come up are dealt with as efficiently as possible. This should increase the first-time fix rate.
2. CACAR work instructions.

Requirements:

1. Remote support experts need to be on call during operations.
2. QR codes on all field parts
3. Integrate existing CAD models of components in the AR system.

7.1.5 Appendix E: 03-06-2025 - Interview with CBA analyst Vattenfall (Person E)

Objective:
To assess the potential of Augmented Reality (AR) to reduce the frequency of revisits in offshore wind turbine maintenance by evaluating its impact on technician efficiency and expert availability.

Summary:
A focused meeting between the researcher and a Cost-Benefit Analysis (CBA) analyst at Vattenfall, aimed at exploring how Augmented Reality (AR) could improve operational efficiency by reducing the frequency of revisits in offshore wind maintenance workflows. A key challenge identified was the lack of accessible data on revisit frequency within existing dashboards, which limits the ability to quantify AR's potential impact directly.

To address this, the analyst proposed two complementary approaches: (1) conducting structured surveys with field technicians to gather qualitative insights on AR's perceived value, and (2) manually reviewing a sample of 100 tech tickets to estimate how often revisits occur and whether they could have been avoided with AR-enabled remote support *(both were sadly not realistically achievable within this research budget and given the project timeline).*

The discussion also highlighted the importance of using existing metrics (such as tech ticket volume and repair time) as proxies for evaluating efficiency improvements. The CBA noted that while some turbines experience up to 25 visits per year, a more typical figure is 10–12. The shortage of trained technicians, particularly during peak periods, further underscores the potential value of AR in improving workforce scalability and responsiveness.

Key Insights:
- Revisit data is not readily available in existing dashboards, limiting direct analysis.
- Surveys with technicians could provide valuable qualitative insights into AR's effectiveness.
- Manual review of 100 tech tickets was proposed to estimate revisit frequency and identify avoidable cases.
- Suggested metrics for estimating AR's impact include tech ticket volume and repair time.
- Technician availability is a known bottleneck, especially during peak demand periods, leaning into the **remote expert** support value proposition that l**everages the number of experts** by giving them more reach.
- From general experience of the CBA, typical turbine sees 10–12 visits per year (for any cause); 25 is considered high.

Use Case Highlight:
AR-enabled remote expert support could reduce the need for follow-up visits by allowing real-time diagnostics and guidance during the initial site visit. This would improve first-time fix rates and alleviate pressure on limited expert resources.

7.2 Interview Analysis and Insights

Stakeholder interviews revealed several high-potential applications of AR within OWF O&M, with three primary use cases emerging: digital work instructions, video-based training, and remote expert support.

Digital Work Instructions were consistently identified as a promising AR workflow. While advanced implementations involving 3D CAD models and Context-Aware Cognitive Augmented Reality (CACAR) using QR code recognition were discussed, even a basic capability to access and navigate work instruction PDFs hands-free was considered a genuine improvement over current tablet-based workflow. This enhancement is particularly relevant in offshore environments, where technicians operate under time constraints and safety-critical conditions.

Video Database and Training was highlighted as a long-term benefit of AR deployment. As maintenance activities are recorded, especially complex or infrequent repairs, these video logs can be curated into a structured training repository. Such a database would support technician upskilling and knowledge dissemination across geographically dispersed teams. Importantly, stakeholders emphasised that this knowledge should be distributed rather than centralised, ensuring that field technicians benefit directly from accumulated expertise.

The most frequently cited and strongly supported use case was **AR-Enabled Remote Expert Support**. This application leverages AR's core strengths, hands-free operation, real-time video communication, and visual annotation, to facilitate expert guidance during field interventions. The primary objective of this system is to reduce the number of visits required to resolve technical issues, **thereby improving first-time fix rates, subsequent revisits and ultimately reducing turbine downtime and operational costs.**

For each use case, stakeholders identified specific technical requirements and organisational barriers to entry. These include hardware ruggedisation, software integration with existing ERP systems (Vattenfall uses SAP), user ergonomics, and privacy safeguards.

A critical insight from the interviews is the importance of revisit frequency as a key performance indicator for the business case. However, this metric is not currently tracked within Vattenfall's tech ticket dashboard environment. Revisits are not explicitly linked to initial service requests and identifying them would require manual analysis of ticket content and chronology. This data gap presents a challenge for quantifying the baseline problem and estimating the potential impact of AR-enhanced workflows.

Nonetheless, the revisit rate remains central to the business case. The value of AR tooling is directly proportional to its ability to reduce revisit frequency. Estimating the number of revisits avoided, either as a percentage of total revisits or on a per-platform basis, enables a first-order approximation of the operational benefit. If the average cost of a revisit (including both logistical expenditure and production loss due to downtime) is known, then multiplying this figure by the estimated number of avoided revisits yields a preliminary benefit calculation. This has been performed in Chapter 9.

Given the low TRL of AR in this context as shown in Chapters 4 through 6, such a first-order estimation is appropriate and sufficient for the current stage of investigation. As the project progresses through

Vattenfall's Stage-Gate innovation framework (see Figure 3), more accurate cost-benefit analyses and empirical validations will be required to support further investment decisions.

7.3 Technical and Organisational Feasibility

The semi-structured interviews conducted with Vattenfall stakeholders revealed a consistent set of technical and organisational requirements, as well as barriers to adoption, which are summarised and analysed below using the Technology Acceptance Model.

7.3.1 Technical Requirements

To ensure successful deployment of AR-enhanced workflows in offshore wind farm maintenance, the following technical prerequisites must be met:

- **Hardware**: Ruggedised, voice-controlled AR headsets equipped with integrated cameras and microphones, suitable for offshore environments.
- **Software**: Field Service Management (FSM) platforms capable of supporting real-time video communication, annotation features, and seamless integration with enterprise systems such as SAP or Salesforce.
- **Connectivity**: Reliable offshore network infrastructure (Wi-Fi, LTE, or satellite) to support low-latency, high-bandwidth communication essential for remote expert support.
- **Data Management**: Secure cloud-based storage solutions for session recordings, incorporating metadata tagging and retrieval functionalities to support documentation and training.

7.3.2 Organisational Considerations and Barriers to entry

The organisational context at Vattenfall presents several barriers, constraints and requirements that must be addressed to enable successful AR implementation:

- **Scepticism:** A clear and compelling value proposition is essential to overcome scepticism and ensure user buy-in, particularly among field technicians. Interviewees consistently indicated that AR should measurably improve task efficiency, reduce error rates, and enhance training outcomes in order to be welcomed.
- **IT Integration Capacity**: Internal capacity for custom integration is limited. Therefore, vendor solutions with pre-configured connectors and minimal engineering overhead are preferred.
- **Privacy**: Continuous video recording raises concerns among technicians, particularly regarding workplace surveillance and data governance. Opt-in policies, clear recording indicators, and anonymisation features (e.g., face blurring) are recommended.
- **Ergonomics**: The device must be easy to use, both UI wise and also hardware wise in confined spaces.
- **Change Management**: Adoption of AR systems requires structured training programmes, early stakeholder engagement, and clear communication of the value proposition to mitigate resistance and ensure alignment with operational workflows.

7.3.3 Technology Acceptance Model

The Technology Acceptance Model (TAM) provides a structured framework for evaluating the likelihood of successful adoption of Augmented Reality (AR) systems by end users (Marangunić & Granić, 2015). It does so by assessing three key constructs: Perceived Usefulness (PU), Perceived Ease of Use (PEOU), and Behavioural Intention to Use (BIU).

Perceived Usefulness (PU):
Stakeholders expressed strong interest in AR for ad-hoc corrective maintenance tasks, particularly in scenarios involving complex or unfamiliar faults. The potential of AR to reduce revisit frequency and improve first-time fix rates was widely acknowledged, especially when expert guidance and field-of-view (FOV) process steps and remote support are integrated. Additionally, AR was recognised for its potential to enhance technician training and documentation practices, particularly through video logging and remote collaboration functionalities. However, it was also emphasised that the **usefulness must be clearly established before widespread user buy-in can be expected.**

Perceived Ease of Use (PEOU):
Ease of use was identified as a critical determinant of adoption. Stakeholders emphasised the importance of intuitive user interfaces, reliable voice control, and ergonomic hardware design. Compatibility with Personal Protective Equipment (PPE) and non-intrusiveness during field operations were considered essential prerequisites for successful deployment in offshore environments.

Behavioural Intention to Use (BIU):
The intention to adopt AR systems is shaped by the combined influence of perceived usefulness (PU) and perceived ease of use (PEOU). Stakeholders indicated that their willingness to engage with AR tools is contingent upon the demonstrable value of the technology in daily operations. This value must be clearly established through pilot studies or empirical validation before widespread adoption can be expected.

7.3.3.1 SCARF methodology

While the Technology Acceptance Model (TAM) provides a structured framework for evaluating user adoption based on Perceived Usefulness (PU) and Perceived Ease of Use (PEOU), it does not fully account for the **social and emotional dimensions** of resistance to new technologies. Furthermore, the quality and accessibility of training programmes, as well as the degree of stakeholder involvement during implementation, were identified as critical enablers of positive behavioural intention. Importantly, social, and cultural factors must be considered.

To address this, the **SCARF model**, developed by Rock (2008), is applied as a complementary lens. SCARF identifies five domains (**Status, Certainty, Autonomy, Relatedness, and Fairness**) that influence human responses to change, particularly in collaborative and operational environments.

These domains are especially pertinent to the implementation of AR at Vattenfall. Technicians may perceive AR as a threat to their **status** if it implies a lack of competence, or to their **autonomy** if its use is mandated without consultation. Concerns about privacy and surveillance may undermine **relatedness**, while unequal access to AR tools could challenge perceptions of **fairness**. Furthermore, uncertainty about how AR will affect daily workflows may reduce **certainty**, leading to resistance even if the technology is functionally sound. These statements are further explained in the table below:

Domain	**Implications for AR Adoption**
Status One’s relative importance to others	Technicians may feel diminished if AR implies, they need help or oversight. Frame AR as a tool to enhance expertise, not replace it.

Certainty Ability to predict future outcomes	Sudden changes in workflows or unclear AR procedures may cause discomfort. Provide clear onboarding, training, and predictable use cases.
Autonomy Sense of control over events	Mandating AR use may reduce perceived autonomy. Allow technicians to opt-in or use AR at their discretion.
Relatedness Feeling of safety with others	AR may feel isolating or intrusive. Use it to foster collaboration (e.g., remote expert support as teamwork), not surveillance.
Fairness Perception of fair exchanges	Unequal access to AR tools or unclear benefits may cause resentment. Ensure transparent communication and equal opportunity to benefit from AR.

Table 2: SCARF model for the implementation of AR at Vattenfall.

The introduction of AR systems must respect the autonomy and professional expertise of field technicians, who are highly skilled and accustomed to operating independently in demanding environments. To ensure acceptance, AR must be framed not as a managerial oversight mechanism, but as a discretionary tool that technicians may choose to employ when appropriate. This means that **opt-in usage**, **transparent communication**, and **inclusive training** is ensured during the implementation phase. This framing is essential to avoid perceptions of surveillance or criticism and to foster a sense of ownership and empowerment among users.

By aligning TAM's cognitive dimensions with SCARF's social dimensions, a more holistic understanding of user acceptance is achieved, supporting a smoother organisational transition and increasing the likelihood of successful adoption.

7.4 Conclusion

While the AR deployment in OWF O&M is supported by commercially available solutions as shown in Chapter 6, successful implementation remains contingent upon organisational readiness and user acceptance. These are influenced by several critical factors, including structured onboarding programmes, robust privacy safeguards, demonstrable operational benefits, and correct framing of why these tools are introduced to field technicians.

The Technology Acceptance Model (TAM) analysis conducted in this chapter indicates that AR adoption is likely to succeed, provided that targeted change management strategies are employed. Stakeholders expressed a clear preference for intuitive, non-intrusive systems that integrate seamlessly with existing workflows and personal protective equipment (PPE). Moreover, behavioural intention to use AR tools is strongly influenced by the perceived autonomy of field technicians. As deducted from the SCARF methodology, is essential that AR be framed not as a managerial oversight mechanism, but as a discretionary tool that technicians may choose to employ when appropriate. This framing respects the professional expertise of the workforce and mitigates concerns regarding surveillance or criticism.

Ultimately, the findings of this chapter support the null hypothesis, namely that AR will be a useful tool for OWF O&M within Vattenfall, subject to further validation of financial and organisational feasibility. The key value driver for AR usage identified in the interviews is increasing wind turbine availability through reducing the number of maintenance visits. AR can possibly achieve this through three core business process innovations that have been indicated throughout the interviews:

1. **Remote Expert Support**
   Enabling real-time, hands-free collaboration between field technicians and remote experts to improve first-time fix rates and reduce revisit frequency.
2. **Remote Collaborative Training**
   Using AR to deliver immersive, scenario-based training modules that support technician onboarding and skill development across geographically dispersed teams.
3. **AR-Enhanced Work Instructions and Reporting**
   Providing step-by-step digital guidance and automated documentation directly in the technician's field of view to improve procedural compliance and reduce cognitive load.

These processes are in line with the proposed areas where AR can add value in industrial contexts, as indicated in Chapters 4, 5, and 6. The insights gathered here are further analysed in Chapter 8 and form a critical input to the business case development in Chapter 9, providing a foundation for strategic decision-making within Vattenfall's Stage-Gate innovation framework.

8 Candidate Processes at Vattenfall

The ideation phase of the previous chapters has expanded the breadth of knowledge through exploratory research. This chapter initiates the synthesis phase, wherein a focused set of candidate solutions is derived from the accumulated insights. The objective is to identify, evaluate, and prioritise O&M processes within Vattenfall's offshore wind operations that are amenable to enhancement through AR. The analysis is grounded in a triangulated methodology comprising:

1. Synthesis of AR state-of-the-art applications and academic literature in industrial contexts *(see Chapters 4 and 5).*
2. A comparative assessment of commercially available AR-enabled FSM platforms *(see Chapter 6).*
3. Semi-structured interviews with domain experts / stakeholders at Vattenfall *(See Chapter 7).*

The aim is to determine which operational processes offer the highest potential for value creation through AR integration, and to select one for subsequent business case development.

8.1 Identified Candidate Processes

Through the interviews in Chapter 7, three processes emerged as the most promising candidates for AR integration:

1. **Remote Expert Support**
   Enabling real-time, hands-free collaboration between field technicians and remote experts to improve first-time fix rates and reduce revisit frequency.
2. **Remote Collaborative Training**
   Using AR to deliver immersive, scenario-based training modules that support technician onboarding and skill development across geographically dispersed teams.
3. **AR-Enhanced Work Instructions and Reporting**
   Providing step-by-step digital guidance and automated documentation directly in the technician's field of view to improve procedural compliance and reduce cognitive load.

Each of these processes is evaluated in detail in the following subsections, including a SWOT analysis and a comparative scoring matrix to determine their relative suitability for pilot implementation. To determine which operational workflows within Vattenfall's offshore activities are most suitable for Augmented Reality (AR) enhancement, a qualitative evaluation was conducted using the criteria defined in Section 8.1.

8.1.1 Remote Expert Support for Field Technicians

This process involves enabling real-time, hands-free collaboration between field technicians and remote experts via AR headsets. Experts can provide live guidance, annotate the technician's field of view, show documentation, and assist in diagnostics and decision-making without being physically present. This approach is particularly relevant in offshore contexts, where expert availability is already limited and further constrained by constrained by travel time, weather conditions, and safety protocols.

In literature, the term AR remote maintenance is often mentioned, for which Breitkreuz et al., 2022 proposed the following definition: *"AR remote maintenance is defined as a technology that enables two or more users (remote experts and on-site technicians) who are not in the same physical space to create* *a shared view that is enhanced with AR-based communication cues to collaboratively accomplish maintenance tasks"* .

As is the case with the proposed RealWear and OverIT configuration, the integration with Vattenfall's existing SAP infrastructure significantly reduces implementation complexity. The Remote Expert Support functionality offered by this system is natively embedded within the FSM software, enabling video calls and live collaboration **without requiring extensive Digital Engineering resources.** Unlike more advanced AR applications, such as immersive training environments or context-aware work instructions, this use case does not necessitate the design of tailored workflows or bespoke training modules. Consequently, the deployment of AR for Remote Expert Support represents a low-effort, high-impact intervention that aligns well with Vattenfall's current digital capabilities and operational constraints.

8.1.1.1 Why This Process Benefits from AR

The Remote Expert Support process is particularly well-suited for AR enhancement due to a convergence of operational needs, technological capabilities, and organisational constraints:

- **Operational Insight from Stakeholder Interviews:**
  Interviews with Vattenfall personnel revealed that an unknown proportion of revisits are caused by incomplete diagnostics during the initial site visit. AR enables real-time, hands-free collaboration between field technicians and remote experts, allowing issues to be resolved during the first intervention. This directly improves first-time fix rates and reduces the need for costly follow-up visits.
- **Support from Academic Literature:**
  Theoretical studies (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025) confirm that AR systems enhance maintenance performance by enabling live video feeds, visual annotations, and contextual guidance. These features have been shown to reduce procedural errors and improve diagnostic accuracy in complex field environments.
- **Market Readiness of Supporting Technologies:**
  The market analysis (Chapter 6) identified that platforms such as RealWear, when combined with OverIT's FSM software, offer mature, field-tested support for remote expert collaboration. These systems include native functionality for video recording, annotation, and integration with SAP-based work orders, reducing the need for custom development.
- **Strategic Fit in the Offshore Wind Context:**
  Offshore wind operations are characterised by limited expert availability, high revisit costs, and logistical constraints. AR significantly extends the reach of expert personnel, enabling a single expert to support multiple sites per day without travel. This not only improves operational efficiency but also accelerates the development of junior technicians through direct, real-time guidance in the field.

8.1.1.2 Technological Requirements

Successful deployment of AR-enhanced Remote Expert Support in offshore wind maintenance requires the following technical components:

- **AR Headsets**: Rugged, ergonomically designed head-mounted devices such as the RealWear Navigator 520, equipped with high-resolution cameras and microphones. These must comply with offshore safety standards and maintain unobstructed field of view (FOV) for technicians.
- **Field Service Management (FSM) Software**: Platforms such as OverIT must support real-time video communication, visual annotation, and seamless integration with enterprise systems including SAP and Salesforce.
- **Connectivity Infrastructure**: Reliable offshore communication networks (Wi-Fi, LTE, or satellite) are essential to ensure low-latency, high-bandwidth data transmission for live expert support.
- **Data Management**: Secure cloud-based storage for session recordings, ideally with metadata tagging and retrieval capabilities supported by machine learning to facilitate documentation and training.

8.1.1.3 Process Requirements

To ensure operational feasibility and effectiveness, the following process-level conditions must be met:

- **Expert Availability**: Remote experts must be available on-call to support live AR sessions during field interventions.
- **Technician Training**: Field personnel must be trained to initiate, manage, and navigate AR sessions effectively, including basic troubleshooting and escalation protocols.
- **System Integration**: AR session data must be logged and retrievable through existing ticketing systems to ensure traceability and compliance.
- **Escalation Criteria**: Clear guidelines must be established for when AR support should be initiated and when a formal tech ticket should be created if remote resolution is not feasible.

8.1.1.4 Barriers to Entry:

Despite technical feasibility, several organisational and behavioural challenges must be addressed:

- **Limited Integration Capacity**: Vattenfall’s internal Digital Engineering resources are constrained, necessitating low-effort, pre-integrated solutions to minimise implementation overhead.
- **Privacy Concerns**: Continuous video recording may raise concerns among technicians regarding surveillance and data governance. Opt-in policies, visible recording indicators, and anonymisation features (e.g., face blurring) are recommended.
- **Cultural Resistance**: Technicians unfamiliar with AR may perceive the technology as intrusive or gimmicky. Early engagement and framing AR as a discretionary support tool are essential.
- **Change Management**: Structured onboarding, stakeholder involvement, and iterative feedback mechanisms are required to ensure smooth adoption.
- **Ergonomics and Usability**: Hardware must be comfortable for extended use in offshore environments, and software interfaces must be intuitive and non-disruptive to existing workflows.

8.1.1.5 SWOT Analysis

The following SWOT analysis evaluates the strategic viability of implementing AR-enhanced Remote Expert Support:

Strengths

- Reduction in revisit frequency and turbine downtime (as claimed in literature, market research and stakeholder interviews).
- Extended expert reach, enabling support across multiple sites without travel.
- Enhanced technician training and knowledge transfer, particularly for junior staff.
- Hands-free operation, improving safety and task efficiency in offshore environments.

Weaknesses

- Dependence on reliable offshore connectivity, which may be variable across sites.
- Privacy concerns related to continuous video recording in the workplace.
- Medium-high upfront costs for AR hardware fleet and recurring SaaS licensing fees.
- Organisational change requirements, including training, process redesign, and stakeholder engagement.

Opportunities

- Development of a searchable knowledge base from recorded AR sessions.
- Scalable expert support, allowing centralised expertise to be deployed across geographically dispersed assets.
- Improved first-time fix rates, contributing to reduced operational expenditure and increased asset availability.

Threats

- Resistance from field staff or unions, particularly if AR is perceived as a surveillance tool.
- Perception of AR as intrusive or gimmicky, especially among technicians unfamiliar with the technology.
- Risk of poor adoption if the value proposition is not clearly communicated or if ROI remains uncertain.

8.1.2 Remote Collaborative Training

AR-enabled training offers a scalable and immersive solution for technician development across Vattenfall’s geographically dispersed offshore wind operations. Through scenario-based simulations and real-time collaboration with remote trainers, junior technicians can engage in high-fidelity learning experiences that accelerate onboarding and enhance skill acquisition such as presented in Figure 7 and Figure 21.

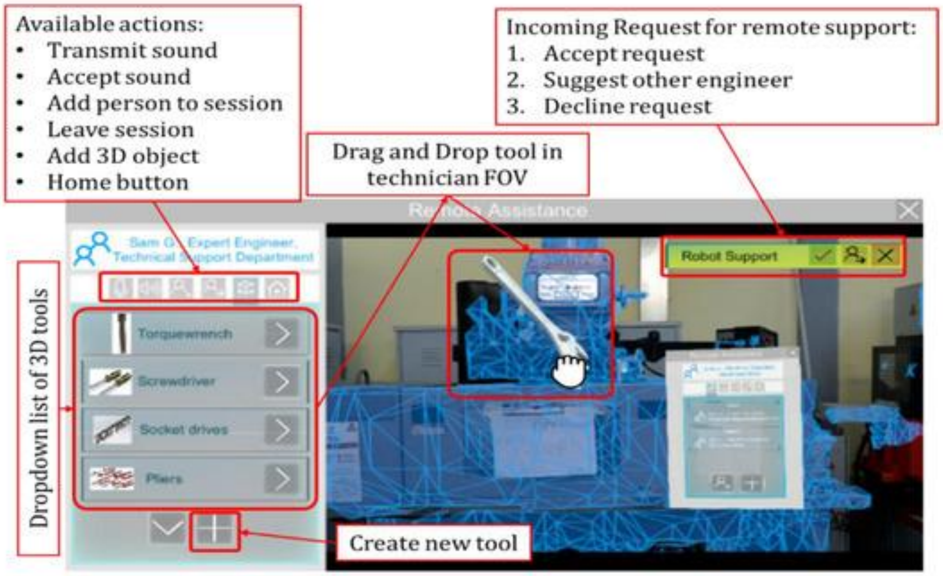

Figure 21: AR workflow creation tool as presented in Mourtzis et al. (2020).

Training sessions may be conducted asynchronously using recorded AR workflows or synchronously through live, interactive modules. These capabilities are particularly valuable in multinational organisations such as Vattenfall, where workforce development must be coordinated across multiple countries and operational contexts.

By leveraging AR platforms that support 3D model interaction, gesture-based navigation, and contextual overlays, training content can be tailored to specific turbine platforms and maintenance procedures. This not only improves knowledge retention but also reduces the need for travel to centralised training facilities, thereby lowering costs and logistical complexity.

8.1.2.1 Why This Process Benefits from AR

- **Stakeholder Insights**: Interviews highlighted the opportunity to curate AR video recordings into structured training modules, facilitating knowledge transfer from senior to junior technicians.
- **Academic Support**: Theoretical studies (Runji et al., 2023; Ong et al., 2023; Malta et al., 2023; Palmarini et al., 2018; Behzadan et al., 2015; Bottani & Vignali, 2019; Fang et al., 2025) consistently support AR’s effectiveness in immersive training and simulation environments.
- **Market Readiness**: Platforms such as Jigspace enable collaborative training using CAD models and remote avatars, enhancing engagement, retention, and contextual understanding on the Apple Vision Pro AR platform. While not suitable to the offshore environment, trainings take place in offices, negating that downside.
- **Operational Fit**: AR reduces the need for travel to centralised training centres, offering a cost-effective and flexible alternative for multinational teams.

Technological Requirements

- High-resolution AR/VR/MR headsets with gesture and voice control (e.g., Apple Vision Pro, Meta Quest).

- Training platforms (such as Jigspace) that support 3D model interaction and remote collaboration.
- Availability of CAD models for turbine components and curated training content. These typically reside with OEMs, and this may require extensive effort to orchestrate and develop.

8.1.2.2 Process Requirements

- Development of AR-compatible training modules tailored to specific turbine platforms and maintenance procedures.
- Scheduling and coordination of remote training sessions across teams and time zones.
- Integration with HR and training systems to track progress and certification.
- Feedback loops to refine training content using field-recorded AR sessions.

8.1.2.3 Barriers to Entry

- High initial effort required to develop and maintain high-quality training content.
- Significant hardware costs, particularly for high-end enterprise-grade AR headsets such as the Apple Vision Pro. But the Meta Quest that costs 1/10th may also work as it provides the same functionality, provided that training software is developed for that consumer-based platform.
- Potential mismatch between simulated training environments and real-world offshore conditions.
- Ergonomic and usability concerns, particularly for extended training sessions.

8.1.2.4 SWOT Analysis

Strengths:

- Scalable training across locations.
- Reduces travel and training costs.
- Enhances engagement and retention.
- Enables asynchronous learning.

Weaknesses:

- High content development effort.
- High hardware costs.
- May not fully replicate field conditions.
- Requires CAD and simulation assets.

Opportunities:

- Build a reusable training library for long-term workforce development.
- Upskill junior staff faster.
- Improve safety and compliance.

Threats:

- Low adoption if content is not engaging.
- Competes with existing training methods.
- Hardware relegated to office use only.

8.1.3 AR-Enhanced Work Instructions and Reporting

This process entails the delivery of digital work instructions directly into the technician's field of view, enabling step-by-step guidance, contextual information overlays, and automated reporting through video or image capture. It aims to reduce cognitive load, improve procedural compliance and accuracy, and streamline reporting workflows as is outlined throughout literature (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025).

Figure 22: CAD models of not only the machines and parts, but also the tools used are required for creating digital field workflows and trainings (Mourtzis et al. (2020)).

Among the candidate processes evaluated, this use case offers the highest potential for improving workflow performance. However, it also presents the greatest implementation complexity. Realising its full value requires extensive digitisation of components, tools, and procedures, as well as significant engineering capacity to translate service manuals and OEM documentation into AR-compatible formats. If libraries of CAD models are readily available from AR service providers, this may reduce the integration burden on Vattenfall (see Figure 22). Nevertheless, the creation of tailored workflows based on known troubleshooting scenarios and procedural steps before any value may be extracted remains a substantial barrier to entry (see Figure 21).

Synergies may be found in newer wind turbine platforms that already possess a high degree of digitalisation, such as those incorporating Digital Twin architectures as part of Industry 4.0 initiatives (Manufacturing Goes Digital, 2019; Bhagwan & Evans, 2023; Mastrocinque et al., 2022; Snidermann et al., 2016; Maio et al., 2023). These newer platforms are more likely to possess structured digital asset libraries, including CAD models and sensor data, which can significantly reduce the engineering effort required to implement AR-enhanced workflows. Even if such digital maturity is not currently present across all assets, the ongoing trend towards digitalisation in the offshore wind sector suggests that these conditions may become increasingly common in future deployments.

8.1.3.1 Why This Process Benefits from AR

- **Interviewees** noted that technicians rely on complex manuals and checklists, often accessed via tablets. AR can overlay step-by-step instructions directly in the field of view, improving accessibility and compliance, ensuring no steps are missed and the technician can work with both hands.
- **Literature** Theoretical studies (Runji et al., 2023, Ong et al., 2023, Malta et al., 2023, Palmarini et al., 2018, Behzadan et al., 2015, Bottani & Vignali, 2019, Fang et al., 2025) confirm that AR reduces cognitive load and error rates by delivering step-by-step guidance.
- **Market platforms** like OverIT supports digital workflows, SAP integration, and automated documentation through AR headsets such as RealWear.
- **Hands-free** access to contextual information improves safety and efficiency in offshore environments, where referring to 1000-page service manuals proves difficult.

8.1.3.2 Technological Requirements:

- Rugged AR headsets with sufficient FOV and battery life or switchable batteries, as shifts can be up to 12 hours.
- FSM platforms supporting digital workflows and SAP integration.
- QR code recognition or Machine Learning object detection for context-aware instructions.

8.1.3.3 Process Requirements:

- Digitisation and modularisation of work instructions (already present on tablets), tailored towards AR workflows (to be implemented).
- Integration with SAP for checklist completion and reporting.
- Training for technicians on navigating AR interfaces.

8.1.3.4 Barriers to Entry

- Existing workflows already use tablets; AR must offer clear added value (is hands free enough)?
- Limited capacity for Digital Engineering. Need to digitise and restructure existing documentation if not done so already (paper service manuals) or lose the advantage.
- Ergonomic concerns (e.g., headset comfort, FOV limitations) especially for long shifts.
- Privacy concerns for video recordings
- User comfort and ease of use

8.1.3.5 SWOT Analysis

Strengths:

- Improves accuracy and consistency of field work.
- Streamlines reporting and documentation.
- Enables contextual access to manuals and instructions, showing the right step at the right time and place.
- Hands-free operation enhances safety and efficiency.

Weaknesses:

- Requires digitisation of existing documentation.
- May face resistance if perceived as redundant.

- Ergonomic limitations of current hardware.
- Limited benefit if not integrated with workflows.

Opportunities:

- Enhance procedural compliance and accuracy.
- Reduce reporting time and errors.
- Integrate with predictive maintenance systems.

Threats:

- Technician resistance to new tools.
- Hardware limitations in offshore conditions.
- Lack of integration with legacy systems.
- Resistance against video recording (in general or facing scrutiny for minor safety violations).
- Limited capacity for Digital Engineering for the tailored work instructions.

8.2 Comparative Evaluation

To determine the most suitable candidate process for implementation within Vattenfall's activities, each use case was assessed qualitatively against four criteria, reflecting both technological and organisational dimensions:

- **Operational Value Potential**: The extent to which AR integration could reduce downtime, improve first-time fix rates, or enhance technician productivity.
- **Technical Feasibility**: The compatibility of the process with current AR hardware and software capabilities, including environmental constraints and IT integration requirements.
- **Implementation Complexity**: The anticipated effort required to adapt existing workflows, train personnel, and integrate AR systems into the digital infrastructure. Also, the effort required in not only IT integration but also Digital Engineering capacity required for designing tailor made AR experiences such as trainings and 3D enhanced workflows are considered.
- **User Acceptance and Ergonomics**: The likelihood of adoption by field technicians, considering ease of use, safety, perceived utility, and professional autonomy.

The table below summarises the qualitative assessment of each candidate process against the defined criteria with a score of 1 (low) to 5 (high), with the total score indicating overall suitability:

Process	Value Potential	Technical Feasibility	Implementation Complexity	User Acceptance	Overall Suitability
Remote Expert Support	4	5	5	5	19
Remote Collaborative Training	3	4	3	4	14
AR Work Instructions & Reporting	5	4	1	3	13

Table 3: Qualitative assessment of each candidate process against the four criteria.

8.2.1 Commentary

- **Remote Expert Support** emerges as the most viable candidate (total score of 19) for initial implementation. It leverages existing AR software and hardware ecosystems (5), requires minimal Digital Engineering effort (5), and aligns well with operational needs (4). Calls between technicians are already performed, and simply enhancing that functionality ensures high user acceptance if implemented correctly (5). The functionality, primarily video-based remote collaboration, is widely supported and readily deployable, making it a low-effort, high-impact solution.
- **Remote Collaborative Training** offers strong technical feasibility (4) and high user acceptance since it is introduced in existing office-based trainings (4), which is a less risky environment for user acceptance than during the operations itself. However, the impact of training on an AR headset versus on a PC may be effective but may not impact Vattenfall's bottom line as much as ensuring higher wind turbine availability does (3). Furthermore, its implementation requires significant investment in content development and 3D modelling, but not so much as converting all existing workflows (3).
- **AR Work Instructions and Reporting** presents high operational value (5), fits AR's capabilities to a real-world problem (4) but is the most resource-intensive to implement (1). The transformation of existing documentation into modular, AR-compatible workflows requires substantial engineering capacity, which is currently limited within Vattenfall. Without this foundational work, the benefits of AR integration cannot be fully realised. User acceptance hinges on the sound technical implementation of AR enhanced work instructions and user experience / comfort the most with this process (3).

8.3 Selected Process: Remote Expert Support

Based on the comparative evaluation presented in Section 8.2, **Remote Expert Support** emerges as the most promising candidate for AR implementation within Vattenfall's OWF O&M activities. It offers a high-value workflow that simultaneously addresses operational inefficiencies and workforce development challenges.

This process is selected due to its strong alignment with stakeholder priorities, theoretical support in the literature, and the availability of mature market solutions. It directly targets high-impact issues such as revisit frequency and first-time fix rates, while also enhancing expert availability and facilitating workforce development due to live coaching by experts on complex issues.

Unlike other candidate processes, Remote Expert Support requires minimal Digital Engineering effort. Its core functionality, real-time video collaboration, is natively supported by most AR-enabled FSM platforms such as OverIT in combination with RealWear and does not necessitate the development of custom training environments or digitised work instruction libraries. This makes it particularly suitable for early-stage deployment, where resource constraints and organisational readiness are critical considerations.

The business case developed in Chapter 9 will aim to qualitatively describe the operational benefits of this process and assess its economic impact through first-order financial modelling. This will support strategic decision-making within Vattenfall's Stage-Gate innovation framework and inform the design of a pilot implementation.

9 Business Case

This chapter presents a comprehensive business case for implementing AR in Vattenfall's OWF O&M activities, with a focus on the **Remote Expert Support** process identified in *Chapter 8* as the most promising candidate for AR enhancement.

9.1 Operational Benefit

The primary operational benefit of AR-enhanced Remote Expert Support lies in its potential to increase the **first-time fix rate** and reduce the frequency of subsequent turbine revisits during unplanned maintenance events. This is achieved through three mechanisms:

1. Preventing the creation of follow-up service requests ("tech tickets") by enabling more accurate troubleshooting during the initial intervention.
2. Improving the quality and completeness of tech tickets, thereby reducing the need for second or third visits due to missing or ambiguous information.
3. Facilitating targeted remote support during the first revisit, which can resolve outstanding issues and prevent further interventions. Collectively, these mechanisms contribute to reduced operational costs (fewer total visits) and turbine downtime (issues resolved earlier), with direct implications for Vattenfall's profitability as demonstrated in the financial modelling (Chapter 9).

9.2 Methodology

The business case serves as a key deliverable of this thesis and is intended to not only provide a much-needed addition to the field but also functions to support Vattenfall's Product Innovation team in progressing through the Stage-Gate innovation model. The analysis integrates findings from the literature review, market analysis, stakeholder interviews, and candidate process synthesis to assess the value proposition, process transformation, financial viability, user acceptance, and organisational alignment using multiple frameworks. This should assist management in an informed decision on whether to pursue further development into this technology or not.

By combining a **technology-driven** perspective (grounded in AR capabilities and market maturity) with a **customer-centric** approach (reflecting operational needs and user context), a hybrid business model is developed. This model reflects both the **offer-side potential** of AR systems and the **demand-side requirements** of Vattenfall's O&M operations.

The business case is constructed using a multi-framework approach to ensure both academic rigour and practical relevance:

- **Business Process Modelling Notation (BPMN)**: to visualise current and proposed workflows.
- **Business Model Canvas (BMC)**: to describe the organisational structure of the proposed AR-enhanced process.
- **Value Proposition Canvas (VPC)**: to align AR capabilities with technician needs.
- **Lean Six Sigma**: to identify and eliminate process inefficiencies.
- **Technology Acceptance Model (TAM)**: to assess user adoption potential.
- **Stage-Gate Integration**: to align with Vattenfall's innovation governance.
- **Cost–Benefit Analysis (CBA):** to form a (high-order) estimate financial viability.
    - **Scenario and Sensitivity Analysis**: to explore uncertainty and risk.

9.3 Business Process Modelling Notation

The Business Process Modelling Notation (BPMN) is used to visualise both the current (as-is) and proposed (to-be) workflows. The modelling highlights inefficiencies in the existing sequential ticketing process and illustrates how AR integration can streamline diagnostics, reduce revisit frequency, and improve first-time fix rates.

While the process flowcharts as presented internally at Vattenfall (initially shown but redacted from the thesis due to sensitive Vattenfall data) provide much detail, the aim of the method presented here is to provide a high-level overview of the old and new process, and how exactly AR fits in as an enhancement.

9.3.1 Old Process

Currently, Vattenfall's offshore maintenance operations rely on a sequential, ticket-based workflow as initially shown but redacted from the thesis due to sensitive Vattenfall data. When a technician encounters an unfamiliar issue, a technical support ticket is generated and escalated to engineering teams through a Tech Ticket. This already means a revisit since a reply takes days, not minutes. Due to incomplete field data or diagnostic uncertainty, multiple site visits may often be required, each incurring substantial costs in terms of logistics, downtime, and personnel hours.

9.3.2 New Process

The proposed AR-enabled workflow introduces real-time remote collaboration between field technicians and a limited number of remote experts, greatly leveraging their expertise by minimising travel time and maximising availability of knowledge.

AR can enhance this process in the following way:

1. The expert may guide a junior technician to do the work instead of being present on site, reducing the travel load by one person.
1. Juniors get trained faster in the field as they get more directions from experts directly through the AR glasses and performing the work themselves instead of waiting for the job to be performed.
2. 1 expert can now <u>support</u> 1 safety check <u>per hour</u> instead of <u>performing 1 per day</u> (figuratively speaking), as he/she does not need to travel to other sites while the team performs maintenance. Instead, the expert can log into another call.

Using rugged AR headsets (RealWear Navigator 520) integrated within Vattenfall's IT infrastructure (using OverIT or Librestream), technicians can initiate live video sessions, during which experts can annotate the visual feed, request specific measurements, and guide troubleshooting procedures. All the while, the technician has both hands free to perform the work, instead of controlling a smartphone with a small screen (compared to the FOV of an AR screen). This approach aims to resolve issues during the initial site visit, thereby reducing the frequency of revisits and improving first-time fix rates.

In some scenarios, this support can be pre-arranged, allowing junior technicians to execute complex workflows under the guidance of remote experts. This not only improves task execution but also aligns with AR's strong value proposition in training and upskilling, making it a dual-purpose tool for both operational support and workforce development. The benefit of this training is two-fold: more junior employees can go into the field earlier, since expert support is more easily accessible, and also, they gain more experience quicker as experts guide them through complex and new tasks. In essence, the number of experts should quickly increase as Juniors are coupled to experts and see a lot of cases which are solved with excellent guidance.

9.3.3 Process Flow Comparison

As-Is Workflow (initially shown but redacted from the thesis due to sensitive Vattenfall data):

1. Field alarm goes off.
2. Alarm type triggers a work order fitting for the problem.
3. **(Visit 1)** Technician identifies issue.
4. Tech ticket created post-shift.
5. Engineering reviews and requests more data.
6. **(Visit 2)** Technician revisits site, updates the tech ticket (post-shift).
7. Engineering proposes solution.
8. **(Visit 3)** Technician returns for final repair.

This process is characterised by delayed feedback loops, leading to wasteful site revisits (and perhaps additional turbine downtime) for the same problem.

To-Be Workflow (Ideal Scenario - Live AR Call on First Visit):

1. Field alarm goes off.
2. Alarm type triggers a work order + scheduled call with remote expert + field technician.
3. **(Visit 1)** Technician identifies issue.
4. Technician AR-enabled live session with remote expert.
5. Expert guides diagnostics and solution.
6. **Issue resolved in one visit.**
7. *Session recorded for training/documentation (secondary benefit)*

This represents the ideal scenario, in which there are minimal barriers to initiating an AR-enabled remote expert support session. However, such immediate availability of expert support may not be feasible during the initial stages of implementation due to organisational, logistical, or resource constraints. As a transitional measure, a stop-gap process can be introduced wherein the creation of a tech ticket triggers the scheduling of a remote expert support session for a subsequent site visit:

Transitional Workflow (Pragmatic Scenario - Scheduled AR Call on Second Visit):

1. **(Visit 1)** Technician identifies issue.
2. Tech ticket created post-shift.
3. Engineering reviews and requests more data.
4. (AR call is scheduled for second visit)
5. **(Visit 2)** Technician revisits site.
6. Technician AR-enabled live session with remote expert.
7. Expert guides diagnostics and solution.
8. **Issue resolved in two visits.**
9. *Session recorded for training/documentation (secondary benefit)*

This approach ensures that the issue is addressed through the AR call before a third visit becomes necessary, while also allowing time for expert availability to be coordinated and for relevant technical documentation or historical data to be reviewed in advance. This staged implementation strategy balances operational feasibility with the goal of reducing revisit frequency and improving resolution efficiency.

9.4 Business Model Canvas

The Business Model Canvas (BMC) is adapted to describe the **AR-enabled Remote Expert Support** process as an internal service within Vattenfall's O&M operations.

While the BMC usually describes entire businesses (i.e. Apple, Microsoft, JPMorgan Chase), it can be used to describe the business model of a product (iPhone, Windows, a mortgage), especially since large companies often target multiple separate customer segments with multiple divisions or product lines. Each product line (goods or services) or company division may have their own separate business model.

If we then view a **business process** within a company as the **product,** then this too can be described by the BMC. In this case, the **AR Enhanced Remote Expert Support** business process is viewed as an **internal service** within Vattenfall.

The BMC shows, **organisationally,** what value is proposed by the new internal business process, how it delivers value to the internal stakeholders (right side), and how this value is created from internal assets and activities, and which goods and services need to be acquired externally (left side) (Osterwalder et al., 2010).

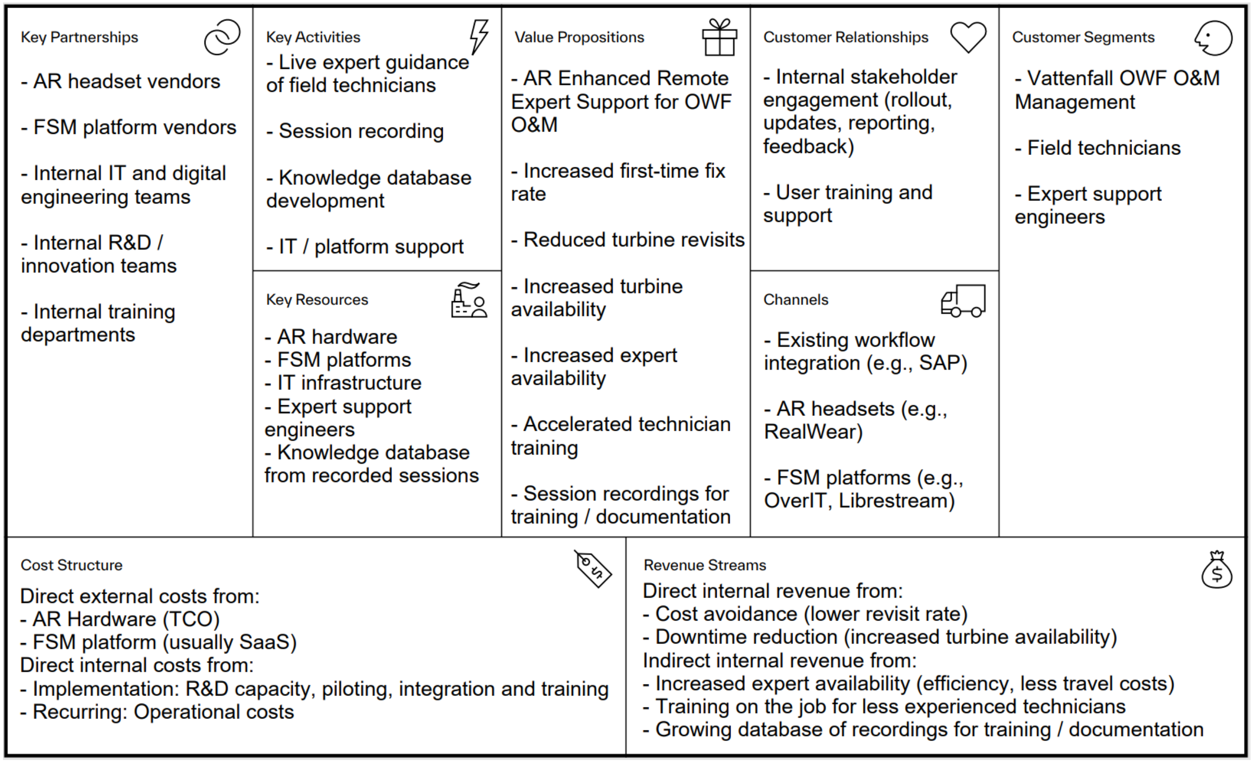

*Figure 23: Business Model Canvas is adapted for usage with the proposed **AR Enhanced Remote Expert Support for OWF O&M** business process. The BMC template is copyrighted under the Creative Commons Attribution-ShareAlike 3.0 Unported License (Osterwalder et al., 2010), (Business Model Canvas – Official Template, n.d.)).*

The key elements of the business model are as follows:

- **Value Proposition:** The AR Enhanced Remote Expert Support business process is expected to enhance operational efficiency during OWF O&M activities. O&M costs, turbine availability and workforce scalability are expected to be improved.
- **Customer Segments:** As these activities are carried out by field technicians and supported by expert engineers, they are seen as the key user segments for this technology. The main beneficiary is identified as Vattenfall OWF O&M management, because their KPI's, such as wind turbine availability, maintenance costs and Quality, Health, Safety and Environment (QHSE) performance, are improved.
- **Channels:** The parts of the technology that the users see are the integration within the workflows, the AR hardware and software platforms, and training. Seamless integration into current systems helps in reducing barriers to adoption, ensuring AR support does not disrupt existing workflows but rather complements them.
- **Customer Relationships:** The type of relationship with the customer is mainly focused on internal stakeholder management regarding integration, training, process improvements and reporting as shown in Section 7.3. Training helps familiarise the workforce with the features of the system, working on examples where it may benefit.
- **Revenue Streams:** The right side of the business model culminates in the revenue streams. 'Revenue' is identified in terms of internal cost reductions, production increase and long-term efficiency effects.
  - Direct:

        - Cost avoidance
        - Downtime reduction
    - Indirect:
        - Increased expert availability
        - Enhanced training on the job for juniors, through more accessible direct expert guidance on complex problems.
        - A growing database of video recordings. If well curated, these videos can be used for high-quality training material or even be integrated in standard AR work instructions over time.
- **Key Resources:** The assets which Vattenfall needs to arrange in house that are integral to support the key activities that deliver the value proposition. Not only are the direct components of the AR system (headset, software) needed, but also supporting resources such as IT, the support experts and the curated database are seen as key assets for the value proposition to work.
- **Key Activities:** Using the key resources available in house, internal activities enable the value proposition from within Vattenfall. These include core functionalities of the AR remote support system, such as the live expert guidance process. Secondary activities are the recording of sessions, managing the knowledge database (which increases the asset's value over time), and supporting the IT infrastructure as well as the FSM platform itself, which is integrates in SAP. These activities warrant the creation of a sound business process within Vattenfall in and of itself.
- **Key Partnerships:** It is more efficient to turn towards 'external' partners for non-core activities and resources. For example, buying / leasing the AR headsets and (customisable) FSM software from external vendors who already completed the R&D and are offering a ready solution with support allows Vattenfall to focus on its core business: operations that ensure power generation and distribution for a competitive price. However, there are some 'internal external' teams present within Vattenfall that are required to provide services in order to support and develop the business process, but are not integral to its operations, such as the digital engineering, product development teams and training teams, who are specialised in the integration processes. Once the business process is in place, those partners are not required in the main operations of the AR system. For this reason, these internal teams are seen as external expertise suppliers.
- **Cost Structure:** The activities, assets and partners on the left side of the business model led to the Cost Structure as described. These are split in directly visible costs, such as billings from the external vendors, and internal costs that require capacity budgeting in order to realise the program. Both external and internal costs require a sounds business model in order for the program to be approved by management.
    - Direct external costs (monetary budget):
        - AR hardware and software
    - Direct internal costs (human resource capacity / budget):
        - Single-occurring costs for implementation (program R&D, digital engineering, training key operators)
        - Recurring operating costs required to uphold the key activities and resources.

While the BMC generates a clear overview of how the business process may be implemented within the organisational context of Vattenfall, it does not paint a complete picture. The other elements of the business case in this chapter serve as more in-depth descriptions of certain aspects of the improved process, such as reasoning why the process needs to be implemented, why the stakeholders are likely to be convinced to adopt the new process, and how likely it is to be profitable.

The BMC does give a clear overview of how the new business process looks like organisationally, but not whether this is currently organisationally and financially feasible. Organisational readiness and financial feasibility are addressed in this chapter by combining different methodologies.

9.5 Value Proposition Canvas

Based on two elements of the BMC, the Value Proposition Canvas (VPC) is a strategic tool designed to ensure alignment between a product or service and the needs of its target users by focusing on how exactly the **Value Proposition** is mapped to the **Customer Segment.** It is particularly useful in early-stage innovation projects, where **understanding the fit between technological capabilities and user requirements is critical for adoption** (Osterwalder, 2014). In this thesis, the VPC is applied to assess the internal alignment between the proposed AR-enhanced Remote Expert Support process and its primary internal stakeholders at Vattenfall.

While the Business Model Canvas (BMC) provides a high-level organisational overview of how the proposed business process is structured, the VPC offers a deeper understanding of the value proposition's relevance to each customer segment. It does so by mapping the **'Jobs to be Done,' 'Pains,' and 'Gains'** of each segment against the **'Products & Services', 'Pain Relievers', and 'Gain Creators'** offered by the AR-enabled solution. This approach supports the identification of the 'product–market' fit and the stakeholder adoption likelihood.

Three distinct internal customer segments are identified for the AR-enhanced Remote Expert Support process:

1. **Vattenfall OWF O&M Management**
2. **Field Technicians**
3. **Expert Support Engineers**

9.5.1 Vattenfall OWF O&M Management

This segment includes operational and asset managers responsible for the performance, availability, and cost-efficiency of offshore wind farms. Their primary concerns are reducing downtime, optimising O&M workflows, and QHSE compliance. They are the key decision-makers for technology adoption and investment, and they evaluate innovations based on the strategic, operational, and financial viability. Therefore, clear business cases are required for the justification of adoption of new business processes such as the one presented in this chapter. The insights presented here are synthesised based on the theoretical background as provided through the MSc. Management of Technology course program. Furthermore, the business process innovation aligns with the 'Operate' area within Vattenfall's internal process landscape (initially shown but redacted from the thesis due to sensitive Vattenfall data).

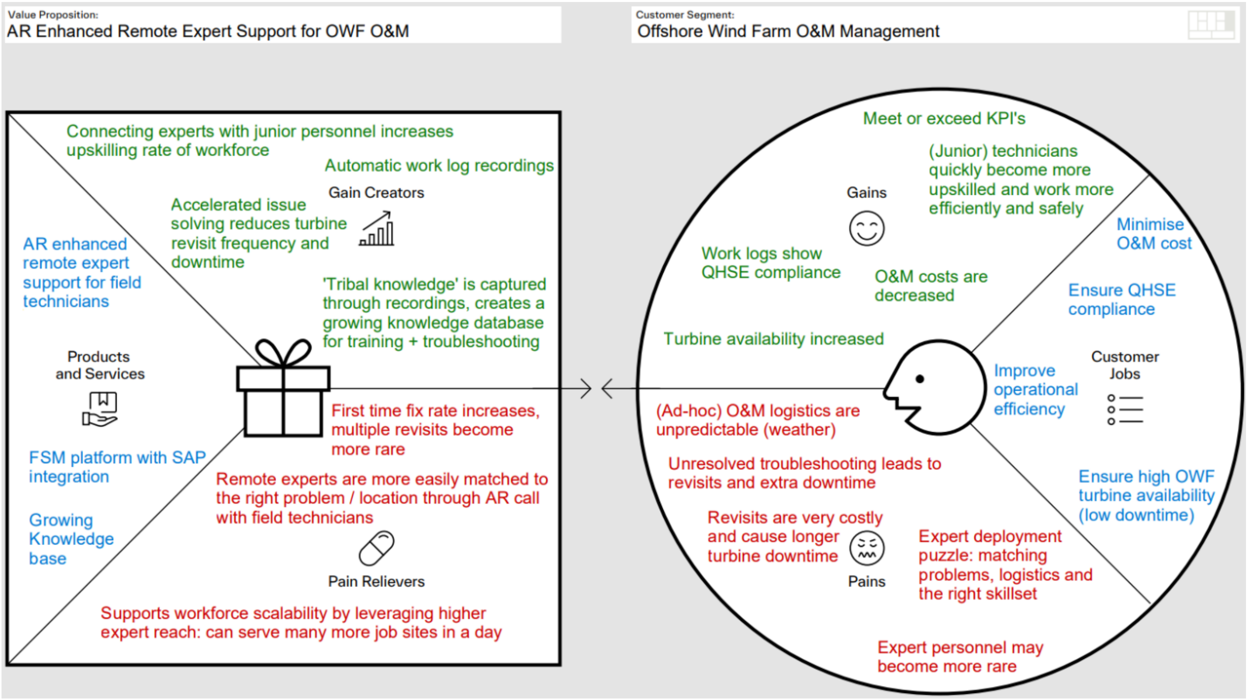

Figure 24: VPC mapping ***AR Enhanced Remote Expert Support*** *(Value Proposition) to* ***O&M Management*** *(Customer Segment). VPC template from (Osterwalder, 2014), (Value Proposition Canvas – Official Template, n.d.).*

Key Characteristics:

- Focused on KPIs like turbine availability, maintenance cost, and safety compliance.
- Interested in scalable, cost-effective solutions that improve operational efficiency.
- Require clear business cases and risk assessments to justify innovative technology adoption.
- *Workforce satisfaction, development, and availability.*

9.5.2 Field Technicians

These are the front-line workers in the OWF O&M activities, responsible for executing maintenance and repair tasks on offshore wind turbines. They operate in physically demanding and safety-critical environments, often under time and weather constraints. Their adoption of the AR system is critical to its success, as they are the primary users of the hardware and software in the field. The insights presented here are synthesised based on the interviews, see Chapter 7.

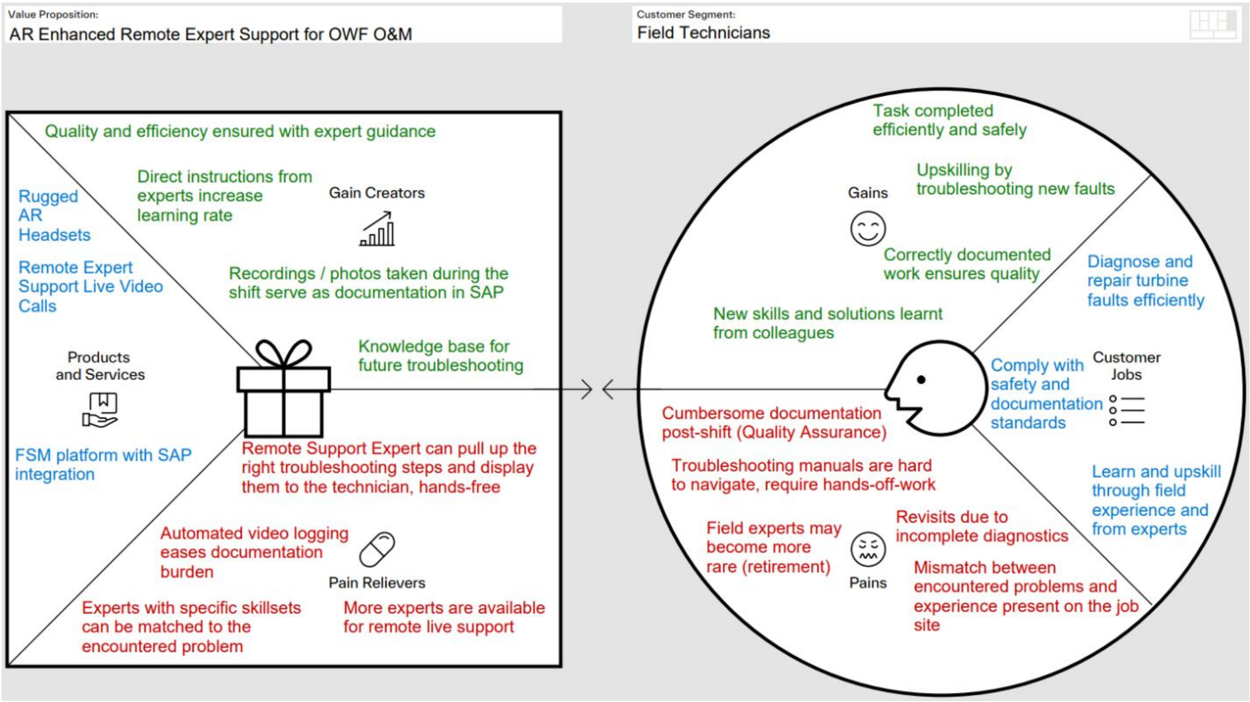

*Figure 25: VPC mapping **AR Enhanced Remote Expert Support** (Value Proposition) to **Field Technicians** (Customer Segment). VPC template from (Osterwalder, 2014), (Value Proposition Canvas – Official Template, n.d.).*

Key Characteristics:

- Require tools that are intuitive, rugged, and enhance task efficiency.
- Value hands-free operation, real-time support, and reduced administrative burden.
- Sensitive to ergonomics, safety, and privacy concerns (video recording).
- Already highly skilled, take pride in their work.

Frame the expert guidance as a tool to use at their discretion to get buy in from field technicians. It is a resource for them to enhance their work, not a tracking tool for management to increase operator efficiency on spreadsheets.

9.5.3 Expert Support Engineers

This group includes technical specialists and engineers who provide remote support to field technicians. They are responsible for diagnosing complex issues, guiding repairs, and ensuring technical accuracy. AR enables them to extend their reach and support multiple sites without the need for travel, increasing their productivity and impact. The insights presented here are synthesised based on the interviews, see Chapter 7.

This customer segment comprises an aggregation of three distinct existing roles for which the value proposition brings similar benefits:

1. **First-line remote support specialists,** who currently provide assistance via conventional voice or video calls using smartphones. These channels offer limited functionality, lacking two-way annotation capabilities and structured documentation workflows. The AR system introduces a more interactive and context-aware support environment, thereby enhancing diagnosis and guidance.

2. **Expert field technicians (these are Senior field technicians),** who under the proposed model transition from on-site roles to office-based remote support functions. Rather than travelling extensively, often requiring up to six hours for a single one-hour specialised task, these experts can now support multiple field operations per day. This shift significantly leverages the utilisation of expert knowledge across multiple sites and facilitates real-time mentoring and upskilling of junior and mid-level field technicians who may now perform these expert tasks under remote AR guidance.
3. **Technical ticket engineers (Technical Authorities),** who are responsible for reviewing maintenance reports and resolving complex or novel issues encountered in the field. In current practice, insufficient information in initial reports can necessitate revisits before further ticket processing and effective troubleshooting can begin. The AR system helps mitigate the first and second revisits in two principal ways:
    1. It enhances the quality and completeness of initial reports through high-quality video recordings captured during the first troubleshooting session.
    2. If a revisit is still needed, it enables scheduled AR-supported diagnostic sessions during follow-up visits, where the technician can accurately indicate the problem and steps taken. Furthermore, this session allows engineers to visually assess the problem and guide technicians through targeted troubleshooting actions. This structured interaction improves the accuracy of data collection and expedites resolution within the engineering team.

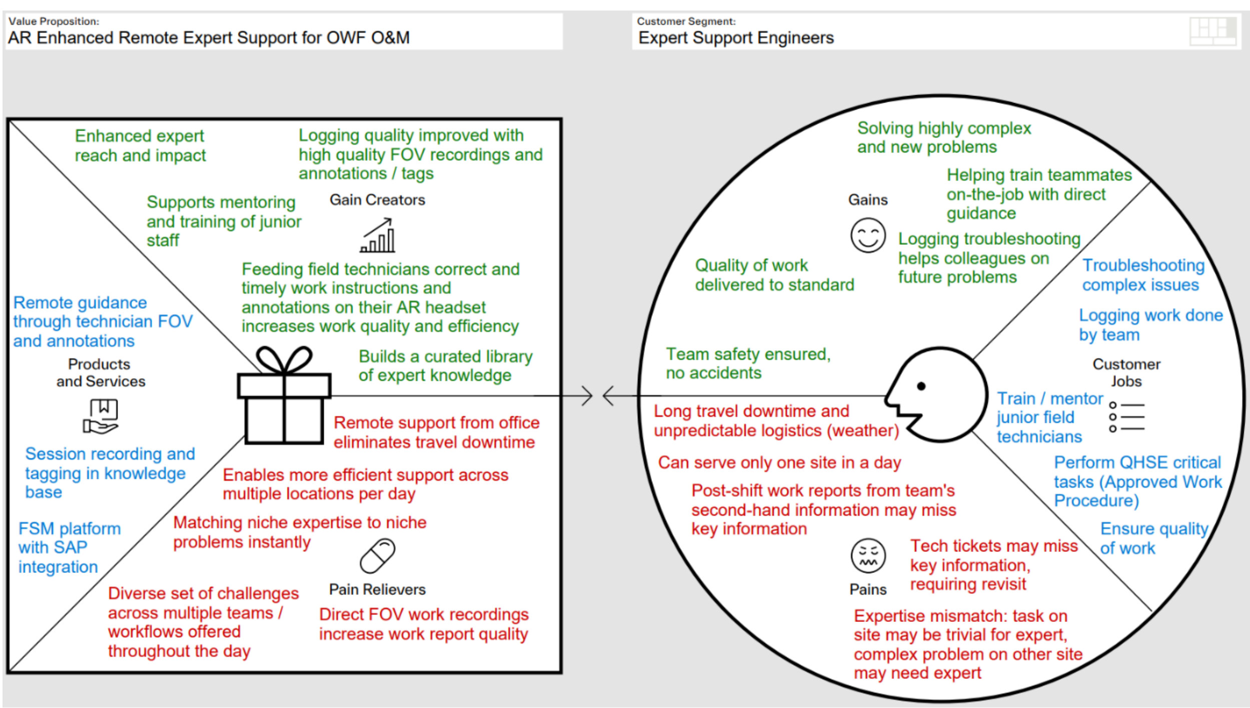

*Figure 26: VPC mapping **AR Enhanced Remote Expert Support** (Value Proposition) to **Expert Support Engineers** (Customer Segment). VPC template from (Osterwalder, 2014), (Value Proposition Canvas – Official Template, n.d.).*

Key Characteristics:

- Need high-fidelity visual input and communication tools to support diagnostics.
- Benefit from reduced travel and increased support capacity.

- Play a key role in training and mentoring junior technicians through recorded sessions and live guidance.

9.5.4 Conclusions and Implications

The VPC analysis confirms a strong alignment between the proposed AR-enhanced Remote Expert Support process and the needs of all three internal customer segments. Each segment derives distinct but complementary value from the system, reinforcing the business case's robustness. For management, the system offers measurable operational and financial benefits. For technicians, it enhances task execution and learning. For expert engineers, it increases reach and efficiency.
This alignment suggests a high likelihood of adoption, provided that implementation challenges (privacy, ergonomics, and IT integration) are addressed through targeted change management and stakeholder engagement strategies.

9.6 Lean Six Sigma

By applying Lean Six Sigma to the AR-enhanced Remote Expert Support process, this section seeks to identify and quantify the sources of waste and variation in the current workflow, and to propose targeted interventions enabled by the AR enhanced workflow.

Lean Six Sigma is a hybrid methodology that seeks to improve process <u>efficiency</u> and <u>quality</u> by combining the focus of **Lean manufacturing** on <u>waste elimination</u> with **Six Sigma's** emphasis on <u>reducing process variation</u> and <u>improving quality.</u> Originating from <u>Toyota's production system</u> and <u>Motorola's quality control</u> initiatives respectively, the combined framework has become a cornerstone of operational excellence in asset-intensive industries (George, 2002; Liker, 2004, "Lean Six Sigma," 2017, Shimp, 2023). Its structured approach is particularly suited to environments where both cost efficiency and reliability are paramount, such as OWF O&M at Vattenfall.

In **Lean**, the primary objective is to eliminate non-value-adding activities, often referred to as "waste," which are categorised under the **TIMWOODS** acronym: **T**ransport, **I**nventory, **M**otion, **W**aiting, **O**verproduction, **O**verprocessing, **D**efects, and **S**kills underused. **Six Sigma** complements this by applying statistical and analytical tools to identify and reduce process variation, thereby improving consistency and predictability. The integration of both methodologies into the **DMAIC** cycle: **D**efine, **M**easure, **A**nalyse, **I**mprove, **C**ontrol provides a structured framework for continuous improvement.

The application of Lean Six Sigma within this thesis is justified by the nature of the operational inefficiencies observed in OWF O&M (Shimp, 2023), particularly the troubleshooting revisits as identified in Chapter 7 and 8. These revisits represent both **waste (unnecessary transport and waiting time of personnel, additional turbine downtime and redundant processing)** and **variation (inconsistent documentation and diagnostics leading to unpredictable revisits)**, making the framework highly relevant. Furthermore, the offshore context amplifies the cost and operational impact of inefficiencies, reinforcing the need for a structured improvement methodology. Additionally, the Lean Six Sigma methodology seems to align with existing process improvement models currently executed within Vattenfall (initially shown but redacted from the thesis due to sensitive Vattenfall data).

9.6.1 Following the DMAIC Framework

9.6.1.1 Define

Clearly defining the problem, project goals and stakeholders should give insight in the project scope and provide a high-level view of the process.

Problem Statement:

OWF O&M at Vattenfall requires multiple site revisits due to incomplete diagnostics, limited expert availability, and inefficient documentation. These revisits increase downtime and operational costs.

Goal:

Reduce the number of revisits and improve first-time fix rates through AR-enabled remote expert support.

9.6.1.1.1 Stakeholders:

As shown in the BMC in Section 9.3 and the VPC in Section 9.5:

- O&M managers
- Field technicians
- Expert support engineers

9.6.1.2 Measure

How can the number of revisits be measured? This is a key metric that absolutely is required to be measured. Currently, several similar metrics are tracked in SAP, but not this one (Appendix F). Can it be expressed as a percentage of total visits? What are the underlying causes of these revisits, and what contribution do these individual causes each have to the negative outcome? What is the cost of these revisits, and what is the potential benefit of a process improvement?

9.6.1.2.1 SIPOC Diagram

The key elements of the current process are captured in the **SIPOC** diagram: **S**upplier, **I**nput, **P**rocess, **O**utput, **C**ustomer.

Supplier	Input	Process	Output	Customer
- Field technicians - Expert engineers - O&M management - IT systems (SAP) - OEM documentation	- Fault reports - Work orders - SAP Tablets - Expert availability - Logistics - Service manuals	1. Fault detection 2. Troubleshoot 3. *Success* 4. Work report *Or if unsuccessful:* 5. Tech ticket 6. Revisit 7. Work report	- Complete or incomplete maintenance task - Manual work reports - Tech ticket backlog - Revisit backlog - Downtime	- OWF Asset Owner - O&M management - Field technicians - Expert engineers - Technical ticket reviewers

Table 4: SIPOC Diagram for the current O&M process within Vattenfall.

9.6.1.2.2 Cost of Poor Quality

The Cost of Poor Quality (COPQ) method describes the economic consequences of failing to meet the process goals. This lists the costs associated with the revisits.

Data must be gathered to understand the extend of the current problem, find the baseline performance metrics, and identify areas of improvement.

Key metrics to the business case are:

- **Operational cost** per revisit
    - Number of turbines at Vattenfall
    - Average turbine visits
    - Revisit rate (% of visits)
- **Downtime cost** per revisit:
    - Turbine downtime per revisit (downtime response time)
    - Cost of downtime (production loss)

Note that operational inefficiencies such as revisit-related costs and turbine downtime have a direct impact on Vattenfall's net profitability. **Revisit costs increase the total operational expenditure without offsetting gains, while production losses represent foregone revenue without any compensatory reduction in Cost of Goods Sold (COGS).** Unlike conventional manufacturing, but quite in line with oil and gas production, wind energy generation incurs negligible marginal costs once infrastructure is operational; therefore, **any interruption in output** does not yield savings but **results in a pure loss of net profit.** This economic structure underscores the importance of minimising downtime and improving maintenance efficiency to protect net margins.

9.6.1.2.3 Net benefit of the project

Benefit of the proposed process improvement:

- Avoidable revisits with AR, yielding:
    - Cost savings in revisits
    - Avoiding production loss

9.6.1.2.4 Data collection

The qualitative investigation of these key metrics is a top priority, as the benefit over cost ratio is a key driver for the project's justification.

As currently many of these metrics are unknown, it is hard to set a baseline for the extend and the variability of the current problem. Interviews indicate that dashboard overviews for turbine visits exist, but revisit events for the same problem are not connected to one another and therefore not logged.

Even tougher is the estimation of how impactful the AR solution will be in mitigating these key metrics, as the effectiveness of AR solutions has not been widely documented in scientific literature, only in marketing material. This is a key limitation of the value proposition in this thesis.

The operational cost per visit should be able to be investigated relatively easily, as these should be accounted for in yearly reports. The **total** cost of downtime should be accounted for as well, but **attributing the downtime cost to revisit delays** is expected to be a more difficult analysis as well, given that the revisit delays are not logged. A Pareto diagram would be helpful, as it indicates the contribution of each root cause to the revisits, but there is not enough information available about the root causes to create such a diagram at this moment.

9.6.1.3 Analyse

Representing one of many available tools within Six Sigma's analysis methodologies, following Lean's **TIMWOODS** principle and the information gathered throughout this thesis, the waste types are identified as follows:

Waste Type	Manifestation in Current Process	AR Mitigation
Transport	Expert travel to offshore sites	Remote support via AR
Inventory	Backlog of unresolved tech tickets	Faster resolution reduces backlog
Motion	Technicians switching between work and docs	Hands-free AR interface
Waiting	Delays between ticket creation and resolution lead to **turbine downtime**	Real-time expert input
Overproduction	Unnecessary revisits	First-time fix via AR call
Overprocessing	Manual documentation	Automated video logging
Defects	Misdiagnosis, incomplete repairs	Expert-guided troubleshooting
Skills underused	Junior techs underutilised; Expert techs can serve only 1 job site per day	On-the-job training via AR support, experts serve multiple sites remotely

Table 5: TIMWOODS waste analysis for the current O&M process at Vattenfall.

Each type is expanded here:

- **Transport:** In the current process, the full team including experts travel to the site. Often, travel can take up the majority of the workday and the expert needs to perform specific tasks such as work area preparation (safety checks) before the team can begin the rest of the tasks at hand. This travel for the experts is eliminated in the proposed process, as they now remotely guide the team on these preparations, allowing the expert to serve multiple sites a day.
- **Inventory:** The amount of unresolved tech tickets can be reduced by
    - Not creating as much by solving more in the field directly with ad-hoc remote expert support
    - Solving more tech tickets with scheduled AR calls with expert engineers
- **Motion:** During troubleshooting, paper-based or tablet PDF-based service manuals are often used. Finding the correct pages / instructions in these manuals can be performed in the background by the support engineer, who sends these work instructions directly to the field technician's AR headset while that person keeps performing the hands-on work.
- **Waiting:** The real-time expert input lowers the number of (re)created tickets as more problems are troubleshooted ad-hoc and/or are solved directly on the first revisit with a scheduled AR call with an expert on that specific problem. This greatly reduces the turbine downtime if successful.
- **Overproduction:** The higher the number of visits per problem are needed, the higher the operational costs will be. The AR enhanced maintenance process mitigates the number of visits.
- **Overprocessing:** AR headset videos can serve as documentation for the work done (either automated or manually post-processed by support engineers, mitigating the need for field

technicians to generate manual reports post-shift and increasing the accuracy of the descriptions at the same time (no time delay, high-resolution video).

- **Defects:** As the field teams now have more easy access to the expert resources, the quality and accuracy of the work should increase, leading to a reduced number of misdiagnoses and incomplete repairs.
- **Skills underused:**
  - (More widely available) **mid-level field technicians** can take perform higher-level (certified) tasks more often under expert guidance through the AR remote support system, which additionally leads to faster upskilling of the workforce**.**
  - (More scarcely available) **expert technicians** can now serve many more job sites as the focus is now entirely on supporting the highest-level critical workflows per request anywhere in the field through the remote AR system without any travel time.

9.6.1.4 Improve

The proposed AR-enhanced Remote Expert Support process of this chapter directly addresses the inefficiencies identified by the TIMWOODS method above. Summarised, the key improvements are listed here:

Proposed Solution:
Deploy rugged AR headsets integrated with FSM software enable:

- Live expert guidance of critical workflows and troubleshooting
- Video logging for training and documentation

Expected Improvements:

- Increase in quality of work and documentation.
- Increase in first-time fix rate.
- Reduction in tech ticket creation.
- Reduction in revisits.
- Reduced expert travel.
- Shorter training cycles for junior and medior technicians.
- Growing knowledge database.

As can be seen, several frameworks are applied here. Firstly, non-value-adding steps are removed from the process (such as a reduction in tech ticket backlog, expert travel time, and the number of revisits). However, several frameworks usually performed within Lean Six Sigma are not applied on this solution yet, but are recommended to do so in order to improve the quality of the improvement:

- FMEA analysis on the new process / brainstorms with stakeholders for potential failure points
- Poka yoke sessions to brainstorm on how to make the new process fool proof
- Pilot testing
- Resistance to change
  - Mitigate by training, change management (feedback sessions)
- Comparing old and new. measure the effectiveness of the new system against the benchmark.

- Use hypothesis testing as a formal approach to discover whether there is a statistically significant change between the two approaches, or whether it can be attributed to the inherent variability of the two processes.

9.6.1.5 Control

In this step establishes the measures that ensure quality control of the improved process over time.

- Define KPI's and track via dashboards (revisit rate, AR session usage, tech ticket creation, travels avoided, downtime avoided, knowledge database usage).
- Use quality control charts that track and determine control limits for these KPI's beforehand so that measurements may indicate whether the improved process stays within these bounds, or that something is happening that influences the outcome beyond these limits.
- Setup process owners and establish AR usage protocols and escalation criteria when corrective action is needed due to an out-of-control signal observation.
- Training programs that align with workforce needs to ensure buy-in.
- Ensure user feedback is analysed and implemented accordingly to maintain constant improvements and acceptance.

9.6.2 Conclusion

The framework also supports the business case development by providing a systematic basis for impact assessment. Through the DMAIC cycle, the thesis defines the problem (revisits), measures key performance indicators (revisit operational + downtime cost, revisit prevention rate), analyses root causes (misdiagnosis, travel time, poor documentation), proposes improvements (AR-enhanced remote expert support), and outlines control mechanisms (KPIs, user feedback). This structured approach ensures that the proposed AR solution is not only technologically feasible but also operationally justified and strategically aligned with Vattenfall's innovation governance.

Moreover, the Lean Six Sigma framework provides a rigorous foundation for evaluating the business case of the proposed solution. Through the DMAIC methodology, this framework defines the core problem (revisit inefficiencies), measures key performance indicators (revisit rates, turbine downtime), analyses root causes (limited expert access, poor documentation), proposes targeted improvements (AR-enabled workflows), and outlines control mechanisms (SAP-integrated KPI's, structured feedback loops). This structured approach ensures that the proposed technological intervention is not only innovative but also operationally justified and strategically aligned with Vattenfall's broader digitalisation and efficiency objectives.

9.7 Financial Analysis

This section provides a first-order estimation of the financial viability of implementing Augmented Reality for Remote Expert Support in Offshore Wind Farm Operations & Maintenance at Vattenfall. The analysis is based on publicly available data, stakeholder interviews, and literature, and is intended to support decision-making within Vattenfall's Stage-Gate innovation framework.

It is important to note that the operational inefficiencies addressed in this thesis, specifically revisit-related costs, and production losses, have a direct and measurable impact on Vattenfall's net profitability. The additional operational costs incurred through repeated maintenance visits increase the total cost base of offshore wind farm operations. These costs are not offset by any corresponding gains and therefore reduce the operating margin.

More critically, production losses resulting from turbine downtime represent a direct loss in revenue without any compensatory reduction in Cost of Goods Sold (COGS). Unlike conventional manufacturing, where halted production may reduce variable input costs, the generation of wind energy incurs minimal marginal cost once the infrastructure is in operation. Consequently, any interruption in production does not yield savings but instead results in foregone revenue. This characteristic of renewable energy economics means that downtime translates almost entirely into net profit erosion.

The financial implications reinforce the strategic importance of process optimisation in offshore wind operations. By reducing revisit frequency and improving first-time fix rates through AR-enabled remote support, Vattenfall stands to recover both operational efficiency and lost revenue, thereby enhancing overall profitability.

9.7.1 Scope and Limitations

Due to limited access to internal cost data and revisit statistics, this analysis uses conservative assumptions and ranges. It focuses on **operational cost avoidance** and **downtime revenue loss avoidance** through **reduction in revisit frequency**, which is the most directly measurable benefit. Other benefits, such as improved training, increased expert availability and enhanced documentation, are acknowledged but not quantified in this initial model.

The cost-benefit analysis (CBA) is conducted at the level of an individual offshore wind farm. This granularity is appropriate for operational budgeting and planning, as well as for site-specific investment decisions. Evaluating the CBA at this level offers several advantages: it balances analytical detail with strategic relevance, accounts for logistical and environmental conditions unique to each installation and facilitates comparative assessment across multiple sites. However, this approach may not fully capture portfolio-wide synergies, such as shared digital infrastructure, centralised logistics, or aggregated procurement efficiencies.

9.7.2 Benefits Analysis

Quantifying these losses is challenging. It is currently unknown which specific faults lead to reduced output or full shutdown, how many of these cases involve revisits, and what proportion of those revisits could be avoided through AR support. Due to this uncertainty, the business case focuses solely on the rough estimation of the directly observable cost avoidance associated with reduced revisit frequency, namely operations and downtime.

9.7.3 Assumptions and Variables

This analysis mainly rests on the cost per revisit when a problem is not troubleshooted on the first (or subsequent) attempt. These revisits however do not occur within a vacuum, and logistics planning should be optimised and opportunity based to find the most efficient logistics planning, costs and resource availability wise. Naturally, multiple turbines within a wind farm can be visited during the same operational time window. This means that finding a cost-per-revisit-number is hard to estimate.

Nonetheless, as these metrics should be tracked at Vattenfall, it should be possible to get a rough estimation on the average cost per turbine visit, and thus the marginal extra cost per extra visit should be known. Furthermore, as uptime is considered the most crucial factor of site maintenance, it is expected that the response time to downtime events is rather short, as awaiting the next scheduled visit should be foregone and an extra visit is planned as soon as possible. For example, if a turbine is visited on average once a month, but a downtime event calls for a high priority (re)visit, the response time may be as short as 3 days.

9.7.3.1 Number of Turbines per Vattenfall Offshore Wind Farm

Vattenfall operates over 1,400 wind turbines across five European countries, with a total installed capacity of approximately 6.6 GW (*Business Area Wind*, n.d.). Vattenfall's portfolio includes several small and large-scale OWFs, such as Aberdeen (11 turbines), DanTysk (80 turbines), Thanet (100 turbines) and Hollandse Kust Zuid (140 turbines). These installations typically employ turbines in the 2–11 MW range (*About Our Power Plants and the Production - Vattenfall*, n.d.). This shows there are widely different economics per location.

Estimated number of turbines per OWF: 11-140 turbines per OWF.
Estimated turbine power: 2-11 MW per turbine.

9.7.3.2 Average Maintenance Visits per Turbine per Year

Maintenance activities are categorised into planned preventive interventions and unplanned corrective actions. The interviews suggest that maintenance campaigns are conducted at least once a year on each turbine, but 10-12 visits per turbine yearly is common, and 25 visits would be a lot (Appendix F). Corrective maintenance actions after alarm triggers are the visits this business case is focusing on, as these usually contain the troubleshooting steps that may require revisits.

Estimated turbine visits per year: 1-25 visits/turbine/year.

9.7.3.3 Revisit Rate

The revisit rate refers to the proportion of maintenance visits that necessitate follow-up interventions due to incomplete fault resolution, secondary failures, or logistical constraints. Empirical studies indicate revisit rates between 15% and 25% for offshore wind assets (Shafiee, 2015), with higher rates observed in early operational years or under adverse weather conditions. For this business case, a conservative 10-50% is considered.

As this is one of the most uncertain metrics, the effect of this change will be modelled though a sensitivity analysis.

Estimated revisit rate: 10-50%

9.7.3.4 Avoidable Revisits through Augmented Reality (AR)

Digitalisation initiatives, particularly AR-assisted maintenance, have demonstrated potential in improving first-time fix rates and reducing revisit rates. AR enables remote expert guidance, real-time diagnostics, and enhanced technician training. Due to there being little to no case studies available for the application of AR in OWF O&M, as a conservative estimate, AR is assumed reduce revisit rates by 10–50%, based on AR - FSM software supplier marketing material in Chapter 6.

As the efficiency gain from enhancing processes with AR is difficult to estimate, this is one of the most uncertain metrics. For better clarity on the effect of this metric, the effect of this change should be modelled though a sensitivity analysis.

Estimated Avoidable Revisits through AR: 10–50% of total revisits

9.7.3.5 Operational Cost per Revisit

The cost of a revisit encompasses vessel chartering, technician deployment, equipment transport, and administrative overhead (Bosch et al., 2019; Röckmann et al., 2017; *Wind Farm Costs*, n.d.; Dinwoodie et al., 2015). For North Sea operations, revisit costs vary by vessel type and duration:

- Crew Transfer Vessel (CTV): €5k - €10k
- Service Operation Vessel (SOV): €15k - €30k
- **Average revisit cost (including labour)**: €5k - €30k

9.7.3.6 Downtime Cost per Revisit

A primary benefit of AR-enabled Remote Expert Support is the reduction in revisits and the operational costs. However, an equally important, though less directly measurable, benefit is the potential increase in wind turbine availability. In many states of disrepair, turbines operate at reduced capacity or are fully offline, depending on the unresolved technical issue, making an exact figure hard to predict.
Not all wind turbine alarms trigger a full downtime condition.

Some alarms indicate that corrective maintenance may be needed a few months later, while other alarms trigger reduced capacity operation. Naturally, full downtime conditions require corrective maintenance response as soon as possible and are, hopefully, resolved quickly. Usually, the Mean Time to Repair (MTTR) is 1-5 days.

Downtime costs are primarily driven by lost revenue from halted energy production and prevailing electricity prices.

For an 8 MW turbine operating at a 40% capacity factor:

- **Turbine power:** 8MW (*About Our Power Plants and the Production*, n.d.)
- **Turbine capacity factor:** 40% (*Wind Energy in Europe*, n.d.)
- **Electricity price**: ~€100/MWh (first order estimate, *Wind Energy in Europe*, n.d. states around €60/MWh - €100/MWh)
- **MTTR**: 24-120 hours (Saeed et al., 2022, Appendix E)
  Resulting in:
- **Total downtime cost per revisit**: €7.68k–€38.k (calculated)

9.7.3.7 Summary of Assumptions

Parameter	Median	Minimum	Maximum

Number of turbines per OWF	100	11	140
Power per turbine	8MW	2	11
Turbine capacity factor	40%	20%	60%
Electricity price	€100/MWh	€100/MWh	€100/MWh
MTTR	48h	24h	120h
Average visits per turbine/year	10	1	25
Revisit rate	20%	10%	50%
Avoidable revisits through AR	30%	10%	50%
Operational Cost per revisit	€15k	€5k	€30k

Table 6: List of assumed metrics, based on literature findings, market data and knowledge of the researcher.

9.7.4 Scenario Analysis

The analysis is calculated on a per-windfarm basis:

*Total visits = number of turbines * visits per turbine per year*
*Revisits = total visits * revisit rate*
*Avoidable revisits = Revisits * avoidable revisit rate*
*Downtime cost per visit = power per turbine * capacity factor * electricity price * MTTR*
*Total savings = avoidable revisits * (operational cost per revisit + downtime cost per revisit)*

*Total savings = number of turbines * visits per turbine per year * revisit rate * avoidable visit rate * (operational cost + (power per turbine * capacity factor * electricity price * MTTR))*

9.7.4.1 Median

Total savings = 100 * 10 * 0.2 * 0.3 * (€15k + (8MW * 0.4 * €100/MWh * 48h))
Total Savings = 60 * (€15k + €15.36k) = €1.82M

9.7.4.2 Minimum

Total savings = 11 * 1 * 0.1 * 0.1 * (€5k + (2MW * 0.2 * €100/MWh * 24h)) = €655.60

9.7.4.3 Maximum

Total savings = 140 * 25 * 0.5 * 0.5 * (€30k + (11MW * 0.6 * €100/MWh * 120h)) = €95.55M

9.7.4.4 Interpretation

- Under **mean conditions**, AR implementation yields savings of approximately **€1.82 million per wind farm per year**.
- Under **maximum conditions**, savings could exceed **€95 million**, driven by high revisit rates, large turbine counts, and extended downtimes.
- The **minimum scenario** reflects negligible savings, indicating that AR investment should be prioritised for high-activity or high-cost sites.

This wide variation, from negligible benefits to almost **€100 million/y,** indicates that the uncertainty of the financial outcome is very high. However, as shown in the maximum case, it is likely that large wind farms with lots of MW of per turbine, with lots of revisits for structural problems will have high downtime and operational costs. From the analysis shown above, a large efficiency improvement in preventing revisits can therefore have a large effect on the operational profitability of the wind farm. It is expected (and shown below in the sensitivity analysis) that even smaller levels of effectiveness in the reduction of maintenance revisits due to the implementation of AR enhanced remote expert support still yield high levels of operational benefits. As Vattenfall is able to evaluate this business case internally on a wind-farm level case-by-case, it should be able to select a fitting wind farm for a more accurate financial forecast through a Net Present Value (NPV) calculation on the yield of the application of AR tools such as demonstrated in (Dinwoodie et al., 2015). If the likelihood and magnitude of profitability are deemed high enough, this may then lead to a pilot study for validation of the business case, gaining user feedback and proposing further system improvements before deciding for further rollout (or suspending the project) according to the gate requirements in Vattenfall's stage-gate development model.

This scenario analysis suggests that the AR-enhanced Remote Expert Support solution is particularly applicable under the following operational conditions:

- **High revisit frequency due to diagnostic uncertainty:**
  In situations where technicians are unable to fully diagnose faults during the initial site visit, AR enables real-time expert collaboration, increasing the likelihood of resolving issues during the first intervention. This directly improves first-time fix rates and reduces costly revisits.
- **Large-scale wind farms with high power output and significant downtime costs:**
  In high-capacity offshore wind farms, even short periods of downtime can result in substantial financial losses. These sites are typically equipped with advanced digital infrastructure, including sensor networks and integrated monitoring systems, which support AR-enhanced workflows. The availability of structured digital data improves the effectiveness of remote troubleshooting and contextual guidance.
- **New-platform wind farms at the early stage of the asset lifecycle:**
  Assets in the initial phase of the "bathtub curve" tend to experience a higher frequency of commissioning and early-life failures (see (Dijkstra, 2022)). However, these platforms are also more likely to be digitally mature, often incorporating Digital Twin architectures as part of Industry 4.0 initiatives (Manufacturing Goes Digital, 2019; Bhagwan & Evans, 2023; Mastrocinque et al., 2022; Snidermann et al., 2016; Maio et al., 2023). This combination of high failure rates and high digital readiness makes them ideal candidates for AR-enabled remote support and process optimisation.

These conditions define the operational context in which the pilot study is most likely to yield measurable benefits and are all **pointing towards a large capacity wind farm built on a novel platform as the best candidate.** The pilot should be designed to validate the effectiveness of AR under these scenarios and inform broader deployment decisions.

9.7.5 Sensitivity Analysis

Although the project timeline did not permit a full execution of the proposed sensitivity analysis, the methodology is presented here due to its relevance in understanding the robustness of the business case. Sensitivity analysis is essential for evaluating how variations in key assumptions affect the projected benefits of AR implementation.

The analysis focuses on two critical and uncertain variables:

- **Revisit Rate**: Currently, revisit frequency is not systematically tracked in Vattenfall's operational dashboards, making this a key unknown.
- **Avoidable Revisit Rate with AR**: No peer-reviewed studies are available for this specific use case. Estimates are therefore derived from marketing materials of FSM software providers in adjacent industries. Given the lack of empirical validation, a wide range is applied.

A three-dimensional sensitivity model is proposed, where:

- The **X-axis** represents the baseline revisit rate,
- The **Y-axis** represents the proportion of revisits avoidable through AR,
- The **Z-axis** reflects the estimated financial benefit.

The inputs from the three scenarios shown above, **minimum**, **median**, and **maximum,** are modelled to illustrate the range of possible outcomes for each. This approach supports risk-informed decision-making and highlights the importance of empirical validation of the key unknowns through pilot testing.

9.8 Cost estimation for Pilot Deployment

The costs for a pilot study deploying 10 AR headsets are conservatively estimated based on current market prices for headsets, internal resource time and cost estimations, and typical enterprise software licensing models. The breakdown includes the most conservative estimations for initial investment and recurring annual costs.

9.8.1.1 Initial Investment

- **Hardware**
  Estimated at €500 (Meta Quest 3) to €3500 (Apple Vision Pro) per AR headset.
  For this pilot, the upper bound is assumed.
  Total: €35k
- **Integration**
  Estimated at 4 Full-Time Equivalents (FTEs) for one year:
  2 FTEs from IT/Digital Engineering and 2 FTEs from the Business Development team.
  Assumed cost per FTE: €50k/y
  Total: €200k
- **Training**
  Onboarding of 10 technicians for one week. After training, the AR headsets are integrated into the normal workflows, accruing no marginal extra cost in terms of technician time.
  Assumed technician salary: €50,000/year =~ €1,000/week.
  Total: €10k

9.8.1.2 Recurring Annual Costs

- **Software (SaaS Licensing)**:
  Estimated at €500–€2500 per user/y
  Based on general enterprise software licenses, such as M365, Photoshop, SolidWorks (up to €5k/y)

For 10 users, a mid-range estimate of €2500/user/y is used.
Total: €25k/year

- **Operational Support**:
  2 FTEs (1 expert, 1 curator) for remote support and video curation.
  Estimated at **€100k/y**.

Concludingly, for a pilot study with 10 users and headsets, a **total initial cost** of ***€245k*** and a **recurring annual cost** of ***€125k/y*** is expected, amounting to a **total first year cost** of ***€370k*** in the most conservative estimation. The main estimation error is found in the average salary cost, project size and project time, which is estimated at ***€50k/y*** for 6 people who need to develop and operate the pilot system for a full continuous year. This might be a grave overestimation, and the **total first year cost** of ***€370k*** is considered to represent the upper bound for a pilot study with 10 technicians.

9.8.1.3 Note on Full-System Cost Estimation

The cost analysis presented in this section is limited to a pilot-scale deployment involving 10 technicians. A full-scale system-wide implementation across multiple offshore wind farms is not estimated here due to the absence of critical input parameters. These include the number of operational technicians per site, the required number of AR headsets, software licensing tiers, integration complexity, and the scale of IT and operational support infrastructure needed. Without this information, any extrapolation would be speculative and potentially misleading. A detailed cost model for full deployment should be developed following the pilot study, once empirical data on usage patterns, support requirements, and integration effort becomes available.

9.8.2 Pilot Study Proposal

Given the potential upper-bound benefit of ***€95M/y*** under optimal conditions, a pilot study with a maximum estimated cost of ***€370k*** represents a relatively low-risk investment. The pilot would employ a full 10-technician field team supported by 6 FTEs to develop and operate the system under operational conditions, serving to validate the assumptions underlying the business case and assess the real-world impact of AR-enhanced Remote Expert Support.

The pilot should be designed to evaluate the most influential parameters related to the business case: The effectiveness of AR in reducing the revisit rate for ad-hoc maintenance events and its relation to increasing the asset availability. Furthermore, the user acceptance of the AR solution needs to be assessed.

10 Discussion and Recommendations

10.1 Synthesis of Findings

This thesis has demonstrated that Augmented Reality (AR) technologies, particularly in the form of Remote Expert Support, offer tangible operational benefits within Offshore Wind Farm (OWF) Operations and Maintenance (O&M) activities. The research confirms that AR has reached sufficient technological maturity for industrial deployment, yet empirical validation in offshore contexts remains limited. Through a multi-method approach, comprising literature and adjacent industry review (Chapter 4 and 5), market analysis (Chapter 6), stakeholder interviews (Chapter 7), leading to synthesis into a suitable process (Chapter 8) and business case development (Chapter 9), the study has identified revisit frequency as a critical inefficiency in current O&M workflows.

The most promising application of AR is in reducing revisit frequency through hands-free, two-way-video collaboration between field technicians and remote experts to solve ad-hoc problems with less visits as indicated by the stakeholder interviews and synthesis Chapter 7 and 8). This process innovation aligns with Vattenfall's operational priorities and is supported by commercially available solutions such as RealWear headsets and OverIT's FSM platform, which are readily integrated into SAP (Chapter 6). However, the Technology Acceptance Model (TAM) and SCARF principles in Chapter 7 confirm that user acceptance is contingent on perceived usefulness, ease of use, and appropriate framing of AR as a discretionary support tool rather than a surveillance mechanism, which is aligns with the findings from literature (Chapter 4).

The Lean Six Sigma framework applied in Chapter 9 further substantiates the operational inefficiencies addressed by AR, identifying waste types such as transport, waiting, and underutilised skills. The Business Process Modelling Notation (BPMN), Business Model Canvas (BMC), Value Proposition Canvas (VPC) further substantiate the fit between AR enhanced remote expert support and Vattenfall's operational environment.

The financial analysis in Chapter 9 estimates potential annual savings of €1.8M/y per wind farm under median assumptions, with upper-bound scenarios exceeding €95M/y. A conservative estimate of €370k/y is given for pilot with 10 technician and headsets supported by a team of 6 FTE developing and operating the system for a full year, a relatively minimal risk investment given the substantially higher cost savings potential under a wide range of conditions.

This supports a recommendation for pilot testing and further investigation to increase confidence in the Return on Investment (ROI). Such progression is consistent with the requirements of Vattenfall's Stage-Gate model, which mandates structured validation before advancing to subsequent development phases. The report's main recommendation is therefore to pursue further empirical validation of the proposed AR solution through a pilot study at Vattenfall.

10.2 Limitations of the Research

Despite the robustness of the multi-method approach employed in this thesis, several limitations constrain the generalisability and operational applicability of the findings. These limitations are categorised below:

- **Empirical Data Gaps**: Revisit rates and downtime costs are not systematically tracked within Vattenfall's dashboards, limiting the precision of the financial analysis.
- **Small number of interviewees:** With only 5 domain experts interviewed over the course of 6 interview, the insights are not generalisable towards all of Vattenfall's OWF O&M activities.
- **Behavioural Resistance**: Technician scepticism and integration concerns require deeper exploration through empirical case studies and structured change management strategies.
- **Cost Modelling**: The benefits calculation is highly dependent on mostly assumptions based on the researcher's general knowledge from the field, leading to a broad range of inputs. The pilot cost estimation is conservative and lacks granularity. The sensitivity analysis has not been completed but is recommended to be completed for a more complete picture on the scenarios. Collaboration with Vattenfall's Costing & Modelling team is recommended for refinement.

10.3 Recommendations for Academic Research

1. **Empirical Validation**
   Conduct empirical studies on AR's impact on reducing revisit rates for ad-hoc field problems, improving technician performance and workforce development, and the increase in asset availability in offshore wind contexts. A larger set of interviewees may improve insights and provide further suggestions for implementation.
2. **Organisational Readiness**
   Investigate the identified themes surrounding organisational readiness in Chapter 7 for emerging technologies in asset-intensive industries. More interviews with a wider set of stakeholders is recommended to obtain a clearer overview of the insights on AR within the organisation.
3. **Cross-Sectoral Generalisation**
   Explore the transferability of AR-enhanced workflows to other sectors. Particular relevance of the work provided in this thesis should be found in asset-intensive, logistically complex sectors such as oil & gas, onshore renewables and aerospace where the remote nature of assets and complex machinery requires intense geographical relocation of expertise to solve problems.
4. **Total Quality Management**: Consider integrating the methodologies used in the business case into the broader Total Quality Management frameworks to provide a more comprehensive organisational analysis.

10.4 Recommendations for Vattenfall

1. **Cost-Benefit Analysis**
   While the first steps are given in this work, a more intense investigation of key metrics is required to improve the accuracy of the business case. These research papers seem to offer a good starting point: (Carroll et al., 2016; Carroll et al., 2017; Borsotti et al., 2024). Work with the Costing & Modelling team to refine the financial estimates and conduct Return on Investment (ROI) or Net Present Value (NPV) analyses for long-term viability. Reduced risk in outcomes are often required before management approves further steps, such as:
2. **Pilot Implementation**
   Initiate a pilot deployment of AR-enabled Remote Expert Support using **RealWear hardware and OverIT software.** Select a wind farm with high revisit rates and sufficient digital maturity. High

digitisation enables effective AR remote guidance with performance tracking and alarm data, work instructions, and CAD models which can be live accessed and evaluated by the remote expert and sent to the HMD of the offshore operator. A thorough investigation of key windfarm metrics should be performed to find the most suitable wind farm with the highest possible impact from the proposed process improvement. Suggested high-profile pilot sites are identified as:

1. **Aging wind farms** with lots of visits per turbine due to end-of-life conditions of components. However, these may have insufficient digitisation and may show predominantly common faults which are already documented and don't require expert guidance to troubleshoot.
2. **Novel wind farm** platforms with high failure rates. As novel technologies are implemented in new platforms, these may find themselves having high failure rated due to being at the beginning of the bathtub curve. As these are contemporary designs, OEM's certainly have lots of digitised data, CAD models, and service manuals available, perhaps even a Digital Twin. This then allows for critical information to be fed from remote experts to field technicians through AR calls during problem investigations, while logging the video transcripts in the digital service log for review and training.

3. **Stakeholder Engagement**
   Engage field technicians and expert engineers early in the process to ensure user acceptance. Address privacy and ergonomics concerns through opt-in policies and training. Ensure iterative improvements are followed through, giving key users the feeling their feedback has impact. Position the new process as a resource **for** users, not as a control mechanism of users **for** management.
4. **Integration Planning**
   Collaborate with Vattenfall's Digital Engineering and IT teams to ensure seamless integration of AR calls with SAP systems. Start with the highest-impact, easiest solutions first for the first round of pilot studies, ensuring maximum results with minimal (resource) investment and go from there.
5. **Stage-Gate Progression**
   Use the findings of this thesis to support progression to the next stage in Vattenfall's innovation governance model (Chapter 3, Figure 21).

11 Conclusion

This thesis set out to answer the central research question:

How may Offshore Wind Farm Operations and Maintenance activities within the organisational context at Vattenfall NL benefit from the enhanced performance promised by AR technology?

To address this, the study employed a structured multi-method approach for answering the main research question and its sub questions as outlined in Chapter 3, combining literature review (Chapter 4 and 5), market analysis (Chapter 5 and 6), stakeholder interviews (Chapter 7), synthesis into a suitable process (Chapter 8), and business case development (Chapter 9). The research was framed within Vattenfall's Stage-Gate innovation model (Chapter 2, Appendix G, and I) and structured around a hypothesis-testing logic:

- **Null Hypothesis (H0):** AR offers operational value in its current state for the selected O&M processes at Vattenfall.
- **Alternative Hypothesis (Ha):** AR does not offer sufficient operational value in its current state for the identified O&M processes.

The findings of this thesis support the **null hypothesis** and therefore **rejects the alternative hypothesis.**

11.1 Key findings

The study has synthesised that AR Remote Expert Support can potentially significantly enhance technician performance, reduce revisit frequency, and improve asset availability. These improvements **directly impact operational performance and asset availability,** addressing a critical cost driver in offshore wind operations.

This work has been successful in creating a finely grained qualitative and a roughly estimated qualitative business case for an AR enhanced remote expert support process within the operational context of Offshore Wind Farm Operations & Maintenance activities at Vattenfall as a case study. The business case demonstrates strong alignment between AR capabilities and Vattenfall's operational needs while proposing significant financial benefits from first-order quantitative estimations.

- **Technological Maturity**: AR systems are sufficiently advanced for industrial deployment, particularly in remote support and training contexts.
- **Market Readiness**: As described in the Literature (Chapter 4 and 5), AR seems to be technologically matured and market ready for providing tangible benefits towards OWF O&M activities. Vendors such as RealWear and OverIT offer field-ready solutions, though user acceptance and integration remain (manageable) barriers to implementation.
- **Organisational Fit**: Stakeholder interviews confirm strong interest in AR for ad-hoc corrective maintenance, with manageable implementation requirements.
- **Financial Potential**: Under median assumptions, AR-enhanced Remote Expert Support could yield annual savings of approximately €1.8 million per wind farm, with upper-bound scenarios exceeding €95 million.

The proposed AR-enhanced Remote Expert Support process offers several high-potential **benefits:**

- **Operational Efficiency**: Reduction in revisit frequency and improved first-time fix rates.
- **Workforce Scalability**: Increased expert availability and accelerated training of junior technicians with catalogued videos and live guidance
- **Documentation and Compliance**: Enhanced reporting accuracy through video logging and contextual guidance.

Risks and uncertainties include:

- **Integration Complexity**: Limited internal capacity for IT integration may delay implementation and are costly.
- **User Acceptance**: Ergonomic and privacy concerns must be addressed to ensure adoption.
- **Financial Uncertainty**: Benefit–cost ratios remain sensitive to assumptions about revisit rates and downtime costs, but operational wind farm data should be available (see Chapter 9).

11.2 Contribution to the academic field

The thesis contributes to academic literature by addressing a critical gap in empirical AR studies within OWF O&M and provides a structured methodology for evaluating emerging technologies in asset-intensive industries and shows paths towards future research efforts required for advancing the field. It also aligns with Vattenfall's Stage-Gate innovation framework, offering actionable recommendations for pilot implementation and further deployment.

This thesis contributes further to the field by:

- Addressing a critical gap in empirical AR research within offshore maintenance by providing an initial business case for AR in OWF O&M.
- Providing a structured methodology combining novel adaptations of proven frameworks in business analysis: BPMN, BMC, VPC, LSS, and Financial Analysis for evaluating emerging technologies in asset-intensive industries.
- A novel adaptation of the Business Model Canvas to describe a business process innovation rather than a business or product line.
- Empirical insights from stakeholder interviews, synthesised in the frameworks of Technological and Organisational feasibility, Barriers to Entry, TAM, and SCARF.
- Providing strategic recommendations for future researchers and Vattenfall.

The findings are generalisable beyond offshore wind to other sectors facing similar challenges, such as oil & gas, utilities, mobility, and broader energy sectors, see Chapter 6.

11.3 Recommendation for Vattenfall

The main recommendation of this research is to proceed through the Stage-Gate innovation model, following the appropriate process steps for pilot validation and organisational integration.

It is specifically recommended that a **statistical measurement** be conducted on the current (As-Is) maintenance process, with particular focus on the **revisit rate**, which has emerged as the key unknown performance indicator. This measurement should establish a baseline against which the impact of AR-enhanced workflows can be evaluated. In parallel, an **advanced cost–benefit analysis** should be undertaken in collaboration with Vattenfall's Costing & Modelling team to refine the financial business case and assess its robustness under varying assumptions.

If the financial and operational outlook remains positive, a **pilot study** should be initiated. The financial analysis in Section 9.7 and discussion in Section 10.4 suggest that new, high production wind farms that are built on novel platforms are the most likely candidate for a successful pilot study. During this pilot, the key performance metrics of the AR-enhanced workflow, most notably the **reduction in revisit rate due to the introduction of the AR-enhanced workflow,** should be assessed for **statistical significance**. This will provide the empirical validation necessary to support broader deployment decisions and ensure alignment with Vattenfall's innovation governance standards.

12 Artificial Intelligence Large Language Model Prompt Engineering: Disclaimer, Usage and Reflection

This thesis has been independently authored by the undersigned. An emerging field within Artificial Intelligence (AI) Large Language Models (LLM), known as **Prompt Engineering** (Giray, 2023, Chen et al., 2025), has served as a novel **academic writing <u>support</u> tool** throughout this study. Rather than employing AI tools merely as sophisticated search engines, Prompt Engineering involves the deliberate design of clear, effective, and context-aware prompts to elicit refined and relevant outputs from large language models (LLMs). This approach enables the researcher to use AI as a structured brainstorming partner, enhancing the clarity and cohesion of academic writing.

An example of a starting prompt that has been refined over the course of the writing of this research is shown, after which a guided chat session is commenced on the topics at hand:

- Personality: expert specialist AI assistant
- Language: Scientific British English. Use only professional language, with no emoji, no - symbols, regardless of user tone.
- Purpose: [whichever is the purpose at the time, such as: writing draft sections based on these notes, refining these paragraphs, reviewing chapters, and suggesting improvements, brainstorming on subject XYZ, search expansion on topic XYZ, etcetera].
- This business-like assistant behaviour is a permanent aspect of this chat session.

It is important to keep in mind the limitations of these tools such as hallucinations, where human-like output is mimicked, and understanding is feigned rather than grounded in factual correctness and true semantic understanding. In practice this means applying thorough fact-checking and not taking the generated outputs at face value. Other mitigation techniques are required to recognise and overcome LLM shortcomings such as ambiguity, bias reinforcement, overfitting, lack of context, ect. In practice, the AI tool was engaged as an eager but fallible research assistant who is capable of generating ideas and perspectives but requiring careful supervision and validation.

Selected portions of the thesis were refined using Microsoft Copilot, Vattenfall's enterprise-grade version of an AI-based LLM. This tool was chosen specifically for its enterprise-grade data security, in contrast to publicly available 'free' alternatives such as ChatGPT, which has a more open data policy. Copilot was used during the editing phase to improve linguistic precision, paragraph structure, and scientific tone, starting from original insights, data, analysis, synthesis, and notes. The use of AI tools in these contexts was limited to their function as language-enhancement instruments, analogous to conventional writing aids such as grammar checkers or word processors.

Additionally, AI was occasionally employed to explore alternative perspectives, cross reference existing findings or suggest supplementary sources and areas for investigation that may not have been initially captured. These interactions were non-decisive and did not influence the core arguments or conclusions of the thesis. The author's domain expertise and independent research remain the foundation of all substantive content, including conceptual framing, analytical reasoning, and interpretation of findings. At no point was AI used to generate original arguments or content. Rather, it was used as a sparring partner for brainstorming, where good prompting techniques helped with thought organisation, resulting in coherent academic writing. All AI-assisted edits were critically reviewed and revised by the author to ensure that the original intent, context, and academic integrity of the work were preserved and only those deemed relevant and substantiated were incorporated into the final text. The AI's role in this context was supportive, not generative, and **all final interpretations and conclusions are the result of the author's independent analysis.**

While one might argue that AI-generated results are inherently biased, which is a recognised concern in the field of prompt engineering, it is equally important to note that conventional internet search engines also produce highly personalised and biased outputs. These biases arise from tracking cookies, geographical data, IP addresses, and historical search and engagement behaviour. Given that the research was conducted on a Vattenfall-issued PC, continuously connected to the company's VPN over a six-month period whilst performing focused research, it is reasonable to assume that conventional search results were heavily biased by the research context. In this regard, AI-based search expansion may have served as a partial mitigation strategy, offering a broader and less context-bound perspective.

It is recognised that the usage of these AI tools for scientific research may be considered unorthodox. However, the researcher is of the opinion that these new tools allow for a new way of working which must be explored through application. As the scientific community's experience with these tools grows, so too will the development of scientifically rigorous methodologies for applying them. Ultimately, AI LLMs are just another tool in the engineer's toolbox, which needs to be applied carefully and within context.

This statement is intended to provide transparency regarding the responsible and limited use of AI in the preparation of this thesis. It is hoped that this disclosure will contribute to the ongoing discourse on the appropriate integration of AI tools in academic research and writing.

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Appendix A: 25-03-2025: First Visit Vattenfall, Interview with Person A

Role:

Product Manager

Interviews

Consider approach. Do I perform questionnaires? In the beginning phases, the interviews will be open to enquire about the current processes.

How to expand beyond questionnaires? Perhaps use an interview guide?

Ask stakeholders for lower and upper bound of cost estimates (best Guess). Then, you might not need simulations

How about the safety requirements in the processes? Will AR enhance or limit safety?

Prepared questions

Interview with Person A from Vattenfall 25-03-2025 10h00-12h00. Some parts are paraphrased for clarity. Most parts are my own notes from our talk.

- **Questions in bold**
- *Answers in italics*
- Notes in normal text

What candidate processes are there for implementing AR?

Special problems at OWF turbines that need experts to solve. So not routine, planned maintenance, but rather ad-hoc corrective maintenance. This typically is required after an alarm or when a turbine shuts down.

Your manager mentioned you were mapping processes' waste. Could you explain?

This is not entirely true. I tried to identify activities to see if there are wasteful parts which can become more efficient, but there was not enough data logged, therefore this is not applicable to the AR solution.

We made the note here that AR could help generate this data in the long term, through recording of sessions and post processing of the data. This is more of a secondary benefit, however, as a large database of activities can only be realised after a long track record of recording and a lot of effort in post-processing to log/categorise the events that eventually might lead to the elimination of waste. This can then be part of a separate project when the post-processing is complete, as then the needed data is available.

Strengths of AR

As some food for though, I listed the strengths of AR to induce ideas for its possible applications. **Context Aware Cognitive Augmented Reality (CACAR)** is described as the most potent AR solution for assembly/maintenance tasks, as it allows for real-time work instructions to be presented at the right time and placed automatically. This allows for the following benefits:

- Hands free operation
- Lowers cognitive load / allows focus on the task instead of finding instructions
- Remote collaboration with experts is easier through video annotations
- Reduce expert's travel time: they may assist many (novice) operators through video calls from an office instead of travelling to each site.
    - Since there is a shortage of expert technicians, this is actually a great selling point. One expert may be on call and support multiple job sites a day instead of assisting only at one location, greatly increasing the availability of expert knowledge!

These benefits can summarily yield the following direct benefits:

- Reduce the time needed per process
- Reduce the error rate of the process

Reducing the error rate can yield a great benefit, as (1st, 2nd, or 3rd) site revisits are one of the more expensive processes, especially since we are talking about **offshore operations and turbine downtime.** It basically doubles or triples the cost of a required maintenance event. **Obviously, reducing the number of site revisits and increasing the rate of first-time-right repairs directly yields large costs savings!** This will become apparent as described by the case later.

General Brainstorm Session

Key person

A key person for my research could be Person B (Vattenfall Denmark). He could help with the framework of requirements for an AR solution, as he works in first line technical support, which this technology can potentially be aimed at. He understands the operations in which AR might add value, so I could perhaps interview him on this subject.

OverIT

Person A has been involved in the discussion about a SaaS AR solution at Vattenfall. The potential supplier was OverIT. OverIT has previously implemented AR at ENBW. The solution allowed for the purchase of own (compatible) hardware. OverIT would then supply software to enhance video calls (annotate, record, cloud storage). It would help cataloguing working instructions. The working instructions can be used with the AR glasses as-is in PDF form. OverIT system also allows for cataloguing of errors.

Vattenfall did not go through, as there were **internal resource constraints** at Vattenfall for integration with existing systems.

This is where my thesis comes in: (if this is the outcome of the research) a sound business case might help convince management to prioritise resources for AR implementation.

A standalone solution would be preferable, as this requires less internal resource capacity. However, IT still needs to control any software used by Vattenfall, so any solution requires some amount of Vattenfall resources for implementation.

Or course, the above can be captured in the 'implementation costs' of a solution.

Case – New platforms require new knowledge base

New OWF platforms (i.e. new turbine types) lack industry experts for troubleshooting problems. As a platform matures and errors are logged, knowledge is built on how to solve problems. Currently, this knowledge is mostly transferred through word of mouth. The logging (into digital / paper systems) is generally not happening much as this costs technicians time and effort, even though categorised logging might provide benefits in the long term. Understandably so, as after a 10-hour shift on an offshore platform, logging adds extra strain on technicians and might also not be accurate.

The above already gives a clear case for the usage of AR glasses if only for the video logging of all handlings. With (a significant amount of) post-processing, AR video logging might add value as a logging and categorising tool for errors (and potential solutions)! This basically automatically builds an accessible and accurate knowledge base as a platform matures and the number of video logs grows.

Naturally, generating Terabytes of video files does not build value on its own. Therefore, a sound business process should be built to ensure proper video logging, post processing and all secondary needs such as privacy, safety and accuracy are safeguarded. It seems much of the value is to be gained in the (perhaps automated) post-processing, but maybe also during live annotations of (expert) technicians during the recording and the flagging of important moments to ease the post-process.

Key questions

- What is the direct value?
- What is the additional benefit?
- What are the costs?

Case – Stopped turbine

Another business process for Vattenfall is where a turbine is stopped / output reduced and not due to scheduled service with known problems. This may happen due to a few causes:

- An alarm has gone off due to several reasons
  - Overspeed (too high wind speeds (normal operation), or a technical failure (needs repair))
  - Overheat (oil temperature measurements etc)
  - Electrical faults
  - Etc.

If the problem cannot be resolved remotely, technicians must visit the (offshore!) field site to troubleshoot the problem. This brings immense costs in the following ways:

- The operation itself:
  - Supply vessels
    - May be single day or multi day (more expensive)
  - Technicians
  - Parts / tools
- Production loss
  - While the operation lasts
  - Due to limited availability, additional downtime before the operation is commenced.

Obviously, some problems are encountered for the first time, and new solutions must be worked out. This can happen in the field, but otherwise a 'tech ticket' is created where an Engineering Team in the office will troubleshoot the problem and provide a solution. This cannot happen ad-hoc and the (proposed) solution must be carried out in a subsequent visit. Sometimes, additional and unforeseen problems arise, and the cycle repeats itself in another revisit etc.

In other instances, a solution might be known by the company (experts) but not by technicians present at that moment. This too requires a subsequent (expert or after instruction by the same crew) revisit.

Where could AR help in this case? How can primary and secondary benefits be gained?

Benefits:

- An increase in the first-time-fix rate (or reduction in the amount of revisits) would directly gain a great benefit in terms of cost savings, as reworks (and retravels of technicians) are prohibitively expensive!
- Recording of first encounters helps with:
    - The accuracy of troubleshooting in the back office, improving the second-fix success rate
    - Building a knowledge base, ensuring a higher first-time success rate in the future
    - And, more importantly: helps with solving problems ad-hoc through live video calls with annotations with the back office and experts, improving the first-time success rate.

Of course, this requires the proper business processes, capacity allocation and IT infrastructure to ensure correct post processing of videos, logging of errors and solutions and enabling live feeds. Also, a changed business process is needed to make use of AR, i.e. in terms of changed planning and availability of the (technicians, experts and back-office engineers) teams. This process needs to be mapped for a proposed AR implementation.

Costs:

- Implementation costs of new business process
- Implementation costs of IT infrastructure
- What else does Vattenfall need to bring?
- SaaS costs of AR software
- Hardware cost for AR (including write offs, renewal, maintenance etc.)
- Backoffice (expert) capacity, being on call and perhaps idle etc. How much people do you need on support?

Research Value

Where does Vattenfall get value from me and my research?

Person A only had a few weeks/months to review the possibility of AR next to other projects. As there are many projects going on, only superficial analysis can be made, which at some point must be cut off due to uncertainty and other priorities. There definitely seems to be a technically feasible use case, but a lot of questions remain unanswered. As in any company, a sound business case must be present before any further investments (time, money) are agreed by management.

My thesis can contribute here in a few ways

- Identify in more depth the processes, i.e. in terms of
    - Which processes are candidate for AR implementation?
    - The process of AR implementation itself. What business processes must be implemented? How to implement this new process? Which people are needed, and how much capacity in which teams is needed before, during and after implementation?
- Aggregation of more data on how to effectively use AR
    - Interviewing people from tech tickets (the clear use case at this point)
    - Aggregating literature findings to generate a framework of requirements
    - Finding use cases from literature, in this sector or elsewhere.
    - Doing market research; what suppliers are there, what are competitors doing?
- Developing a qualitative business model. Using the business model canvas might prove useful to give shape to the business process that needs to be implemented in the following ways
    - Indicating which (not how much, but perhaps an indication if available) costs and benefits there are. I.e., the **Value Proposition.**
    - Indicating the key activities which are required for the process to function
    - Indicating the key partnerships
    - key resources
- Once the business model has been created, **a collaboration with the cost-calculation team of Vattenfall can help to quantify the business case using their models and cost estimates.**

Deliverable / Definition of Done

To get a clear consensus on when I am finished (see Kickoff)

I will deliver a business case that maps the process and identify key activities / tasks and some indication of costs and benefits and the managing process of how this could work.

Alternative: if the technical feasibility is not there (if found to be the case in the first phase of the research), I could identify the barriers to entry which need to be overcome to get this promising technology implemented at Vattenfall.

Appendix B: 14-04-2025: Interview with Person B

Background & Expertise

Person B is an O&M Technical Expert on offshore platforms X, Y, and Z, with a background as a car and offshore mechanic. Some general knowledge on availability have been discussed, as that is the main driver for O&M activities.

Platform Reliability

Some platforms (types of turbines installed over possibly multiple sites) achieve over 98% availability, with fluctuations of only 1–2%. Others operate at around 95% availability, with a ±5% margin.

Industry prioritizes availability over repair costs due to the high impact of production loss. Downtime leads to significant production losses, making uptime maximisation essential.

AR Technology in Offshore Operations

AR can marginally improve technician efficiency / task speed, but this effect is limited by downtime from safety protocols, weather, and prep time. I.e., a 10-minute improvement on a 60-minute task might help, but sometimes there is multiple hours of downtime or jobs are cancelled due to weather influences.

My analysis: *Meaning, a 10-minute boost in a 60-minute workflow is significant in and of itself, but the impact on an 8-hour shift with 7 hours of downtime might be limited in that the efficiency boost doesn't lead to more sites being able to be visited during a single day. Still, this shouldn't withhold further efficiency improvements for working procedures and a 10-minute speed boost across operations could be very significant!*

Virtual document storage integrated with SAP is identified as the highest-value use case.

Approved Work Procedures (AWPs)

AWPs are detailed safety protocols requiring manual logging and can take around one hour to complete. Generally, an authorised technician (AT) needs to perform the work and create the clearance for the rest of the team to perform the required work on site.

Only one authorized technician performs safety checks, though multiple people may be involved on the job site

AR can streamline AWPs by enabling photo logs, QR code recognition, and step-by-step guidance via smart glasses.

Own reflection: *Although the efficiency gained by AR for such workloads is unknown, the efficiency boost may prove significant: I.e., there might be 1 AT present on a job site for 5 people, meaning that if the AT saves 10 minutes, this applies to a team of 6 people equalling 60 person-minutes saved! Furthermore, it is of my opinion that the downtime technicians usually face should not withhold Vattenfall from trying to improve productivity by introducing efficiency boosting tools such as AR! Rather, given the enormous downtime, every minute on the job counts! The minutes saved on a day with lots of downtime across a team with multiple persons might mean the job gets done today and not tomorrow*

Service Instructions

Manuals are extensive and hard to navigate.

AR can help by providing contextual access to relevant sections, interactive visuals, and voice-activated search.

QR codes on the parts might help identify which exact workflows are needed, in accordance with the provided work package in SAP.

A good digital document storage system which is easily accessible (perhaps through AR) is identified as the highest-value use case.

Current issues:

- Difficulty locating documentation.
- Time-consuming Approved Work Procedures (AWPs).

Potential improvements:

- Digital AWPs with QR code recognition.
    - The headset recognized the QR code on the parts and displays the correct work instructions
- Smart glasses to display step-by-step instructions.
    - The work instructions can be digitised and tailored for use with AR glasses to really make use of the hands-free AR workflow and present detailed step by step guidelines right in the mechanic's field of view
- Photo / video logging instead of manual entries.
    - This helps twofold:
        - Lighten the reporting load which can take a few hours after the shifts / increase the workload during the job
        - Ensures events are logged right away while fresh in the memory of the operator, with minimal distraction from the work itself at happens almost automatically (i.e. everything is filmed).
- Some post-processing might be required to highlight the important parts of video/photos and its relation to the log event.

As a guesstimate: this could save 10 minutes per person, multiplied across teams and workflows. However, the exact impact needs to be determined first through tests.

Remote Expert Support

Currently done via phone; smart glasses are a nice-to-have but not essential.

So, would pivoting towards a process where experts remain on-call in the office to provide field support be preferable? Provided AR could give the right remote communication tool?

On-site experts are preferred due to limitations of camera-based remote troubleshooting.

Critical opinion*: This is exactly what AR could solve! It also greatly improves the reach of experts.*

Training & Video Logging

Suggestion: build a knowledge database by logging and categorizing field troubleshooting. Video logging of fieldwork can support training and documentation of problem-solving. Skilled office workers could do this in the background by analysing footage from the field, so the field workers can focus on the work at hand.

This categorised footage can then be distributed to the workforce through trainings. In this sense, the centralised database greatly helps in knowledge sharing, enhancing the entire pool of technicians with expert knowledge on known problems / solutions.

The Emphasis should be on technician expertise over centralized knowledge. So, distributing the knowledge as much as possible rather than making a nice database no one uses.

Operational Realities

First-Line Support Process:

Planned work → Tool prep → Visual inspection → Execution → Troubleshooting → Completion (if no revisit needed).

Planned Maintenance:

- Weather delays (e.g., wind, lightning)
- Long travel times (30 min to 3 hours)
- Significant downtime despite efficient work practices

Maintenance is often delayed by weather and travel time. Despite efficient work, downtime is significant. Time-saving measures are valuable but must be weighed against operational constraints.

System Integration

SAP integration

Currently, SAP is used: SAP app on tablets synchronises with SAP and provides binary checklists.

Integration with SAP is essential for any AR or digital tool (handles planning, documentation, work instructions, warehousing, etc.).

SAP handles:

- Maintenance documentation
- Warehousing
- Time registration
- Planning and work orders

Current interface: GUI with a service contract (not fully controlled by Vattenfall).

Current Tools

SAP app on tablets:

- Syncs with SAP for the planned work.
- Provides checklists and references to work instructions.

- Provides logs to help with checking of the performed work.

Checklists are binary (yes/no).

Barriers to entry & Adoption Challenges

Privacy Concerns:

- Resistance to being filmed (e.g., PPE violations ‘to get work done,’ general Privacy, Big Brother is Watching feeling).

Suggestions:

- Easy pause/resume recording functionality
- Face blurring

Buy-In: Technicians need a compelling Value Proposition to adopt new tools. The tool should improve workflows rather than be a nice to have gimmick.

High-quality work instructions tailored towards the advantages AR offers are thereby critical for field adoption over the use of standard service manuals. While clunky to use, they are very detailed and provide all necessary information to solve the problem as intended and multiple troubleshooting methods.

Conclusion

Virtual document storage with SAP integration offers the most immediate and scalable benefit for an AR add-on. Work instructions should be tailored towards AR’s strengths. It helps leveraging expert knowledge through video logging and trainings.

Person B remains sceptical of AR since there are already tablets used for digital workflows and smartphones for calling experts.

Appendix C: 24-04-2025: Interview with Person C

What is your role?

Current Role: Platform Asset Manager at Vattenfall, responsible for the operational maintenance of offshore wind assets.

Experience: Over 20 years in the industry, including:

- 15 years in Oil & Gas
- 5 years at TNO as a scientist and consultant, focusing on robotics and emerging technologies for wind energy.

What is your experience with AR?

At TNO, Person C worked on:
- Drones for internal inspections (e.g., inside nacelles).
- Cargo drones (notably with Person F).
- AR/VR training simulations.
- AR glasses for field applications.

TNO has conducted multiple tests with 8–9 different AR/VR systems.
Mixed results: some systems were ineffective, while others showed promise.
Person C has been involved in evaluating these technologies for potential use at Vattenfall whilst working at TNO.

Where do you think the value is in using AR?

Believes AR can add value in almost any area, provided it meets safety standards.
Emphasizes the importance of practicality and safety in implementation.

Barriers to AR Adoption

Privacy concerns (e.g., filming in the workplace)
Safety considerations (ensuring AR does not distract or endanger technicians)

Next Steps

Use Case Development: Identify and define specific AR use cases for offshore wind operations.

Appendix D: 29-04-2025: Interview with Person A

Remote expert support for field technicians

Other example: **Live solving of a Tech Ticket**. Field Collaboration Enhancement. This prevents revisits if (relatively simple) problems can be solved live in the field. Pulling up technical drawings in real time. Allowing technician to solve problem in the field rather than revisit. Getting live feed of information from the Backoffice.

Within Vattenfall, there is usually 1 Technical Authority (TA) on for example Gearboxes. Process:

- Visit 1: Technician finds unknown problem in the field
- Tech Ticket 1 is created
- TA needs extra info to solve Tech Ticket
- Visit 2 **(COSTLY!!)**: Technician performs field measurements to help pinpoint the problem
- Second Tech Ticket 2 is created
- TA identifies the probable problem based on the measurements
- Visit 3 **(COSTLIER!!)**: Technician performs repair based on the probable problem.

Renewed process:

For complicated problems, the number of subsequent visits should be reduced.

- Visit 1: Technician finds unknown problem in the field
- Tech Ticket 1 is created
- TA needs extra info to solve Tech Ticket
- Visit 2 **(COSTLY!!)**: Technician performs field measurements to help pinpoint the problem
- Live collab in the field with Tech Ticket Engineers (or TA)
    - I.e.: Ok make pictures of this
    - Check this
    - Measure this
- Problem is fixed!! Easy!!
- No revisit needed.

BUT? Would the TA be available? Which criteria are needed for an AR call? We cannot solve all problems remote and waste Engineer's time. Specific gatekeepers for AR calls.

But it will solve the things that can be done with a live AR call in the 2nd visit. Instead of going back again and again.

While informal communication already occurs among field technicians, such as calling colleagues who may have encountered similar issues or occasionally using smartphone-based video calls via Microsoft Teams, these interactions are ad hoc and unstructured, and most people are aware of the tribal knowledge present within teams. The introduction of AR-enabled Head-Mounted Display (HMD) systems formalises this process in two key ways:

- **Hands-free operation**: Technicians can receive expert guidance while continuing to work, improving efficiency and safety.

- **Structured support channel**: The AR system provides an official, standardised mechanism for initiating remote expert support, thereby lowering the threshold for requesting assistance and enabling faster problem resolution.
- **Knowledge capture**: Most AR platforms support video recording and metadata tagging. This enables the systematic accumulation of operational knowledge, transforming informal 'tribal knowledge' into a centralised, searchable database that can be used for training, documentation, and continuous improvement.

Next steps:

- Make basic flowcharts of 'process 0' (as-is) and the proposed new process.
    - This should indicate where the value is.
- Schedule Interview Tech Ticket Engineers (Technical Authorities (TA)).

Schedule Interview Field Technicians (how would they feel about AR?).

Appendix E: 23-05-2025: Interview with Person D and Person A

Team and Backgrounds

Person D: From Bulgaria, based in Denmark. Was a Mechanical Engineer at Siemens. Experience in root cause analysis for wind turbines in the field. Currently a Project/System Engineer at Vattenfall. Background in preventive maintenance and VR/AR safety training (e.g., GWO offshore fire training, Jan 2024).

What is the normal process for tech tickets?

Technicians work 10–12-hour shifts, after which they log reports on their laptops. Tech tickets are created using a structured form (e.g., turbine number, work order), with some free-text fields (e.g., problem description, questions to engineers). Tickets are typically created by site leaders or supervisors—not directly by technicians. Engineers review the tickets, investigate the issues, and provide responses. However, economic factors (e.g., weather windows, logistics) are not considered in these recommendations.

Sadly, the tech ticket system is not accessible to the researcher at this point in time.

How often are revisits needed?

Revisit needs often arise when the root cause of an issue is unclear. Engineers then ask for additional information to help uncover the underlying problem. In such cases, experts may need to travel to the site—sometimes for 4–5 days, since Vattenfall operates in multiple northwestern and northern European countries—to conduct root cause analysis. Remote assistance (e.g., via AR or video calls) could potentially reduce or eliminate the need for such travel.

Might AR / video recording be helpful?

AR or video recordings could be useful when engineers need additional information (e.g., measurements or visual checks) after a ticket is submitted. Currently, there is no live communication between engineers and technicians during the ticketing process, and ticketing answers can take several days. AR could enable real-time remote assistance, improving efficiency and reducing unnecessary revisits.

Any idea how often revisits are needed for the same problem? How could such data be made visible?

Person D has worked on the tech ticket dashboard and could assist in visualizing revisit-related data. Person A and the Researcher discussed the need to access this dashboard to analyse **revisit frequency**, as this is a critical number for the research. Sadly, this access cannot be granted. Suggested action: Ask Person B targeted questions to gather relevant data. **Key question: What percentage of revisits could realistically be prevented using AR?**

How many (%) of the revisits could be prevented with the use of AR remote support? Are live calls currently happening a lot during field work?

Not a lot of live (conventional) communication is happening with technicians currently.

Brainstorm: What would be the most effective AR use cases and opportunities in your opinion?

Most effective AR applications may include Hands-free remote support via smart glasses, AR work instructions linked to specific turbine components, Reference Design Structure (RSDP) pop-ups for engineers.

A remote support **hotline** is suggested: AR could be especially valuable before tech tickets are created—during the technical support phase (hotline support). This could work as follows:

- Technical Support Engineers are always on call but not on-site.
- AR calls could offer significant advantages over standard phone or video calls in this context.
- This could help field problems be solved immediately instead of logged as a tech ticket after the shift when it is not fresh in the memory and a revisit is then of course needed.

Speak to tech ticket engineers **Person G, Person H** (team of Person B)

Appendix F: 03-06-2025: Interview with CBA analyst Vattenfall (Person E)

Role

Cost Benefit Analyst at Vattenfall.

Evaluating AR Efficiency and Revisit Reduction

The meeting focused on finding the efficiency of Augmented Reality (AR) in terms of limiting revisits and solving trivial problems during the first or subsequent visits. It was noted that revisit data is not easily found, and the dashboards do not show the number of visits per case.

Key Points Discussed

Person E suggested that surveys with technicians could be most valuable in assessing AR efficiency. Key survey questions could include:

- How much would your efficiency improve with these tools?
- How many problems would be solved by having these tools without needing a revisit because you can call with an expert?

Person A proposed a solution to manually go through 100 tech tickets and log how many need revisits from engineering. This would provide a general estimate of the percentage of revisits. Additionally, the efficiency boost for the first visit and the increased availability of experts through remote support could be evaluated. It was suggested looking at tech ticket count and repair time (hours) to evaluate efficiency.

Observations and Data Points

With regards to visit frequency of wind turbines, it was noted that 25 visits per turbine per year seems high, with 10-12 visits per year being more normal.

Trained technicians are a rare commodity, and peak demand causes a mismatch with the supply of trained technicians.

Appendix G: Product Lifecycle Management Team Workflows

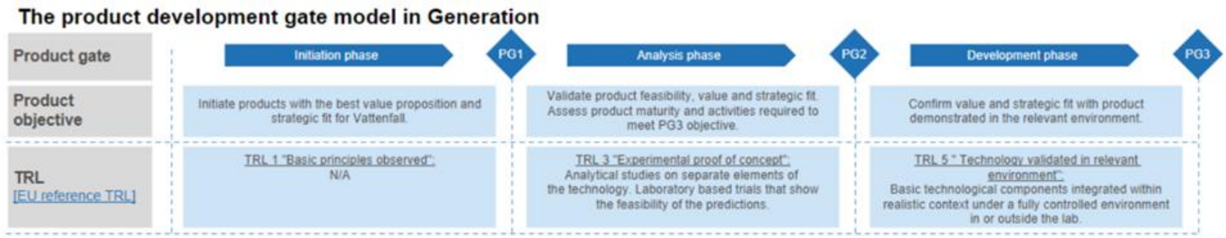

Figure 27: Vattenfall Stage-Gate innovation management model 1/2 (Vattenfall Internal SharePoint Document).

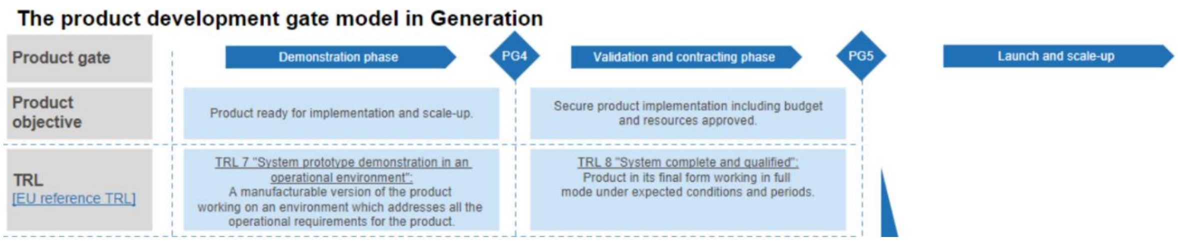

Figure 28: Vattenfall Stage-Gate innovation management model 2/2 (Vattenfall Internal SharePoint Document).