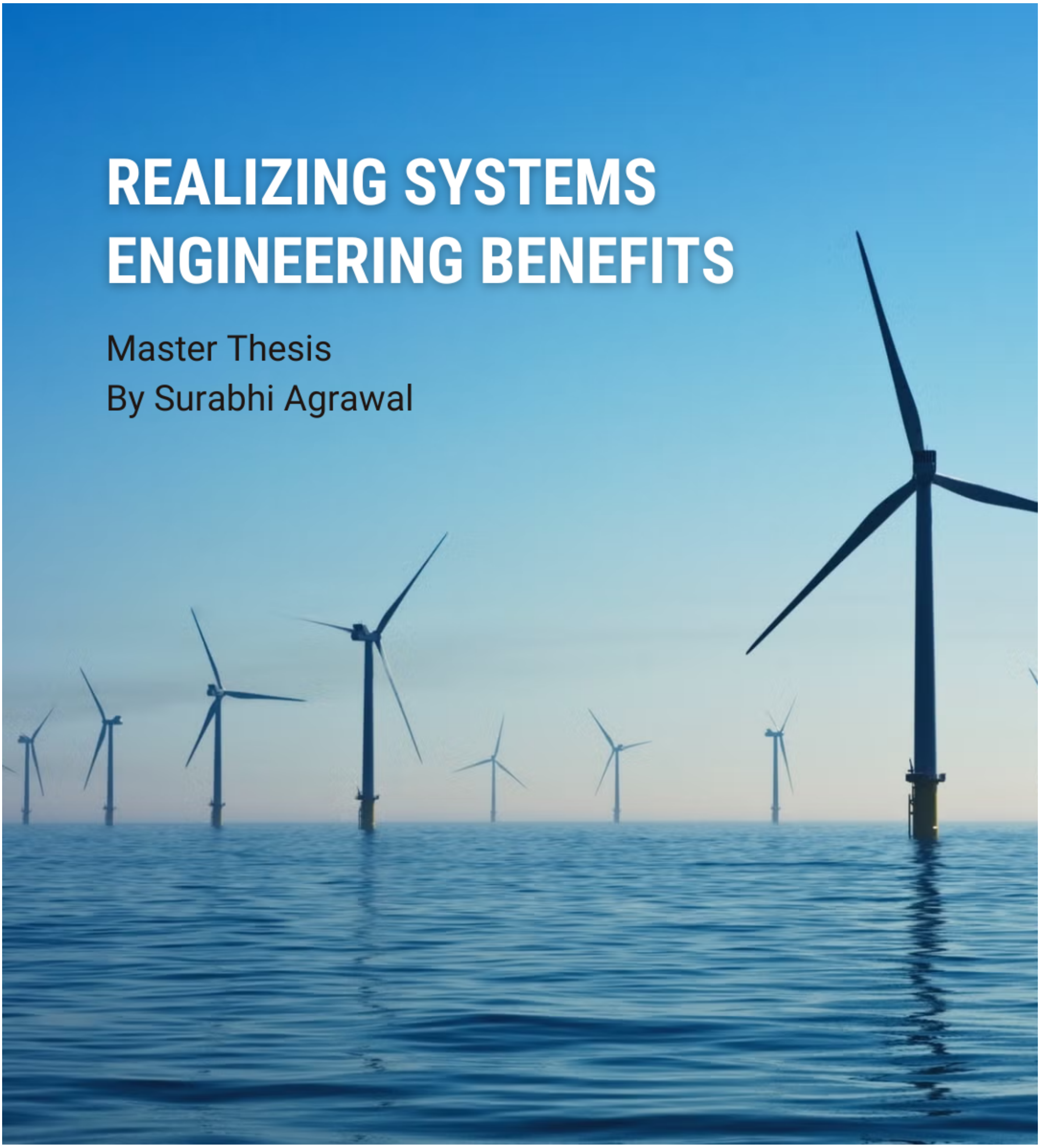

REALIZING SYSTEMS ENGINEERING BENEFITS

Master Thesis

By Surabhi Agrawal

TU Delft

TenneT
Taking power further

DELFT UNIVERSITY OF TECHNOLOGY

MSC. THESIS - CONSTRUCTION MANAGEMENT AND ENGINEERING
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Realizing Systems Engineering Benefits

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Preface

This master's thesis marks the final milestone of my academic journey at Delft University of Technology, where I pursued the Construction Management & Engineering program. In this research, I explored how the benefits of Systems Engineering can be realized in offshore grid connection projects. Conducting my thesis at TenneT offered me a unique opportunity to delve into the dynamic field of offshore projects in the Netherlands. And after months of dedication, filled with both challenges and rewarding moments, this thesis has reached its conclusion. I am deeply grateful to all those who supported me throughout this journey.

First and foremost, I would like to thank my graduation committee: Professor Straub, Professor Ranjith, and Professor Sander, for their guidance and constructive feedback. I am especially thankful to Professor Ranjith for introducing me to this research topic, for his critical questions and thoughtful remarks, and for helping me maintain the scientific integrity of my work. I'm also very grateful to my company supervisor, Alex Trakas, for always being there to help, even with the smallest doubts.

On a personal note, I want to thank my family: my mom, dad, brother, and my home away from home, Shantnav, for their endless support and encouragement. I also appreciate my fellow students and TenneT colleagues for their advice, distractions, and patience during this intense period.

As my time as a student comes to an end, I look back on these two years at TU Delft as a time of growth, learning, and stepping out of my comfort zone. It's been an unforgettable experience.

Summary

The transition to renewable energy is imperative for mitigating climate change and enhancing energy security. Offshore wind has become central to this shift, particularly in Europe, where ambitious climate goals have accelerated large-scale offshore grid developments. The Netherlands, through TenneT's 2GW Program, has initiated the implementation of a standardized high-voltage direct current (HVDC) grid connection system designed to integrate offshore wind energy efficiently. The program aims to establish 14 offshore grid connections by 2032: six in Germany and eight in the Netherlands, each with a 2 GW capacity, amounting to a collective transmission capacity of 28 GW. However, managing the complexity inherent in such large-scale infrastructure projects necessitates structured and effective management methodologies. To address this, Systems Engineering (SE) has been integrated into the 2GW Program to improve scalability, reliability, and overall project delivery. Despite its significant potential, SE faces substantial implementation challenges, as its benefits tend to materialize predominantly in later stages of project execution. This study explores these dynamics by addressing the following research question:

"How can the application of Systems Engineering (SE) address the challenges in offshore grid connection projects and maximize long-term benefits for Transmission System Operators (TSOs)?"

The research follows an evaluation framework that begins by identifying the SE program's rationale, assessing the current status of SE benefits and finally recommendations to help realize these benefits better (concisely summarized in Figure 1). Data was gathered through a triangulated approach: an extensive literature review to build the theoretical foundation, a detailed case study of the 2GW Program, structured document analysis to capture project developments, and semi-structured interviews with key stakeholders. Semi-structured interviews formed the primary empirical data source, conducted with 11 purposively selected participants representing both Dutch and German sides of the program and covering strategic and operational roles. Guided by a thematic framework aligned with the research questions, the interviews explored key challenges in offshore grid projects, expected benefits of SE, and its current status. Data was analyzed using a grounded theory approach in ATLAS.ti. To ensure accuracy of results, respondent validation was conducted, with participants reviewing and confirming summarized interpretations of their input.

Key Findings

Four central themes emerged from the data analysis of interviews: requirements management, V&V, and explicit working enabled by digitalization.

1. **Requirement Management - Strengthening clarity, traceability, and lifecycle alignment:** Implementing structured, SMART, and functionally-oriented requirements aligned with SE principles has improved clarity, traceability, and collaboration across the 2GW Program. Using tools like Relatics and formalizing Customer Requirement Specifications (CRS) enables early conflict detection, reduces late-stage design changes, and supports lifecycle-oriented decision-making, ensuring smoother handovers to Operation and Maintenance teams and minimizing operational disputes.

2. **V&V- Ensuring compliance and reducing delivery risks:** A clearly defined V&V framework - with explicit methods, success criteria, and responsibilities, has reduced contractual disputes, improved accountability, and minimized rework by ensuring systematic contractor compliance. This approach shifts client-side engineers from repetitive document checks to higher-level governance, shortening review lead times and enhancing resource efficiency while safeguarding alignment between delivered solutions and stakeholder needs.

3. **Digitalization - Enabling traceable, transparent, and integrated delivery:** Transitioning from fragmented project-specific data silos to a shared, program-level digital library has strengthened traceability, consistency, and cross-project integration. This explicit, transparent working method aligns with INCOSE guidance, enabling better interface coordination, informed change impact assessments, and long-term data integrity. By ensuring accessible, verifiable information across all actors, digitalization enhances contract management, decision-making, and overall system value.

4. **External factors influencing SE implementation:** The effectiveness of SE in the 2GW Program was shaped by several external factors beyond its direct control. Market dynamics such as "gold-plated" specifications, global supply chain disruptions, and limited contractor availability, drove up costs despite SE's lifecycle-oriented cost optimization approach. The use of FIDIC Silver Book contracts placed quality accountability on contractors, but varying SE maturity, especially among international suppliers, created adaptation challenges. Cultural and organizational change proved slower than anticipated, as tight deadlines led teams to revert to familiar practices, delaying consistent SE adoption. Finally, while program-wide standardization improved efficiency, it also reduced flexibility, as changes to shared requirements required alignment across multiple contracts, adding complexity to implementation.

Recommendations for practitioners

1. Adopt SE in phases - Begin with core elements like requirements management, then expand to V&V processes, configuration management, and traceability to allow learning, tool refinement, and cultural integration.

2. Front-Load requirements engineering –
   - Follow ISO/IEC/IEEE 29148 and ISO 15288 for quality and alignment with other project philosophies (e.g., FIDIC, standardization, program approach).
   - Use standardized templates/taxonomies early and establish robust change control.

3. Retain strategic client-side V&V ownership –
   - Define V&V baselines, expectations, and acceptance criteria early.
   - Optimize verification scope considering cost, time, and risk.

4. Engineer the tools with SE principles – Treat platforms like Relatics as engineered systems, with planned, validated, and iterative development aligned to user readiness and workflows.

5. Embed cultural change management – Pair technical SE processes with strategies that explain both the "why" and the "how" to ensure operational commitment and leadership alignment.

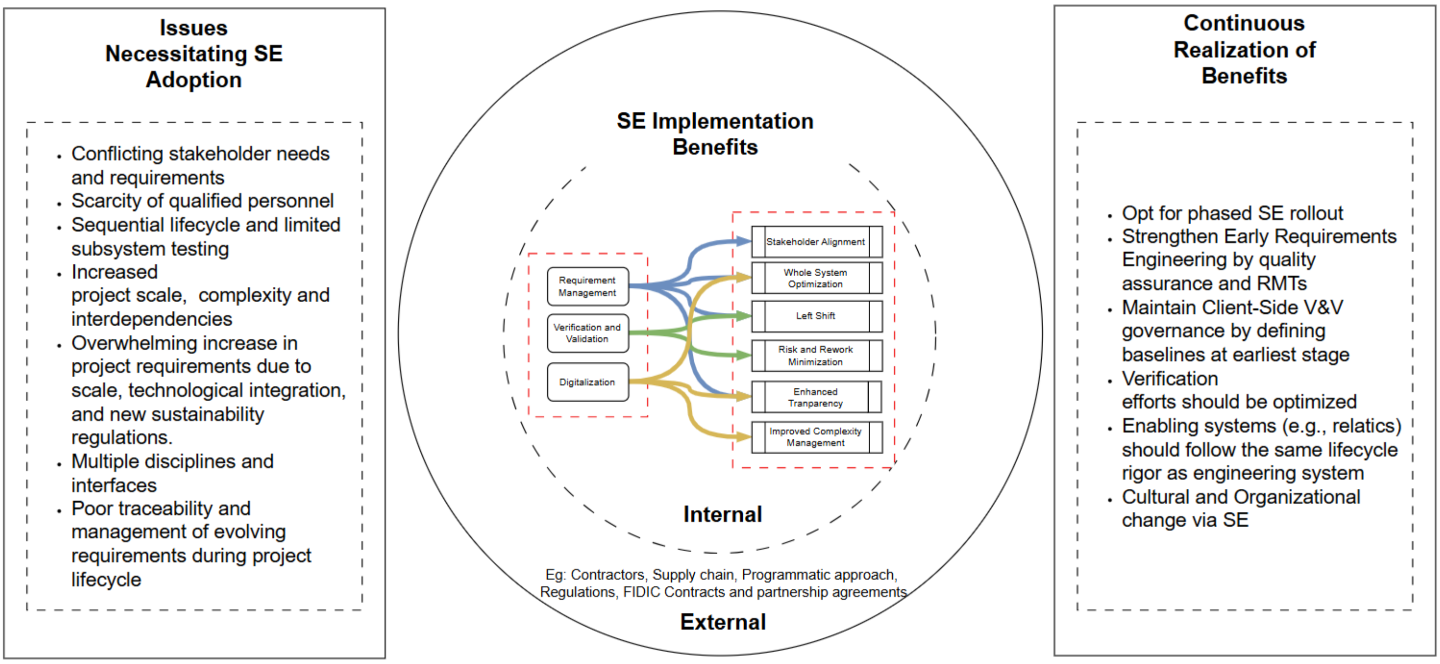

Figure 1: Final Conclusion

Recommendation for Researchers

Future research on SE in offshore grid programs should look at the views of all stakeholders, not just the client. This study focused on the client's perspective, which means it mainly captured benefits seen by the client and may have missed challenges or advantages experienced by contractors. Since contractors play a key role in applying SE in practice, their views are essential for a complete picture of how SE works in real projects. In addition, this research looked mainly at requirements management, V&V, and digital tools during the early stages of the program. Other SE processes were still developing and could not be explored in detail. Future studies should examine these processes later in the program when they are more established, to better understand the full range of SE's benefits.

This research contributes to advancing the role of SE in large-scale energy infrastructure development, ensuring that offshore grid connection projects are delivered efficiently, cost-effectively, and sustainably by TSOs.

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List of Abbreviations

SE	Systems Engineering
HVDC	High-voltage direct current
TSOs	Transmission System Operators
V&V	Verification and Validation
CRSs	Customer Requirement Specifications
SRs	System Requirements
EU	European Union
PM	Project Management
PPT	People Process and Technology
TOTEX	Total Expenditure
LCoE	Levelised Cost of Energy
RMTs	Requirement Management Tools

1 Introduction

The global energy landscape is currently undergoing a significant transformation as the urgency to mitigate climate change is intensifying. Fossil fuels have historically been the backbone of energy provision however their continued use has led to rising carbon dioxide levels and an observable growing trend of global warming (Letcher, 2021). The consequences of climate are extreme: from rising sea levels to extreme weather events, they have created an urgent need for a transition toward sustainable energy systems. In response, governments and international organizations have introduced climate measures that are aimed at reducing carbon emissions, requiring a shift to renewable energy technologies (RET) (Erin Bass & Grøgaard, 2021).

The European Union (EU) has placed itself at the forefront of this global energy transition, setting ambitious goals to become the first climate-neutral continent by 2050. To achieve this target, there is a need to fundamentally restructure the energy system, with renewable sources playing a dominant role. Among the various renewable sources of energy, the share of wind energy in Europe's energy mix is projected to grow (Figure 1.1) from approximately 20% today to over 50% by mid-century (Little, 2024). And with the increasing need to electrify, offshore wind has emerged as a leading solution due to its vast potential, high efficiency, and minimal land-use requirements (Adedeji et al., 2020). The European Commission has acknowledged this crucial role of offshore wind by publishing a dedicated Offshore Renewable Energy Strategy in 2020, outlining the need for 60 GW of offshore wind capacity by 2030 and 300 GW by 2050 (European Commission, 2020). The North Sea has emerged as a critical area for achieving these goals, often referred to as Europe's "green powerhouse." Currently, more than 75% of Europe's offshore wind infrastructure is located in the North Sea, and its full potential is estimated at up to 300 GW i.e., equivalent to approximately 1,000 TWh per year (TenneT, 2025). This capacity could supply the combined annual electricity demand of Germany, Denmark, the Netherlands, and the United Kingdom, covering nearly one-third of Europe's current total demand. Recognizing this potential, the Esbjerg Declaration was signed by Germany, the Netherlands, Belgium, and Denmark in 2022, committing to install at least 150 GW of offshore wind capacity in the North Sea by 2050 (Esbjerg, 2022). This collective effort underlines the key role of offshore wind in achieving Europe's renewable energy targets.

Among the leading contributors to the European offshore wind initiative, the Netherlands has set further ambitious national goals for offshore wind expansion. To align its efforts with the broader European strategy of reducing greenhouse gas emissions and enhancing energy security through increased domestic renewable energy production, The Dutch Climate Act was adopted in 2019, setting legally binding targets including a 49% reduction in greenhouse gas emissions by 2030 (compared to 1990 levels) and a 95% reduction by 2050 (Government of the Netherlands, 2025). As per the policy, the offshore wind energy is expected to play a central role in this transition, with the government aiming for at least 70% of the nation's electricity to be generated from renewable sources by 2030. The Netherlands' strategic access to the North

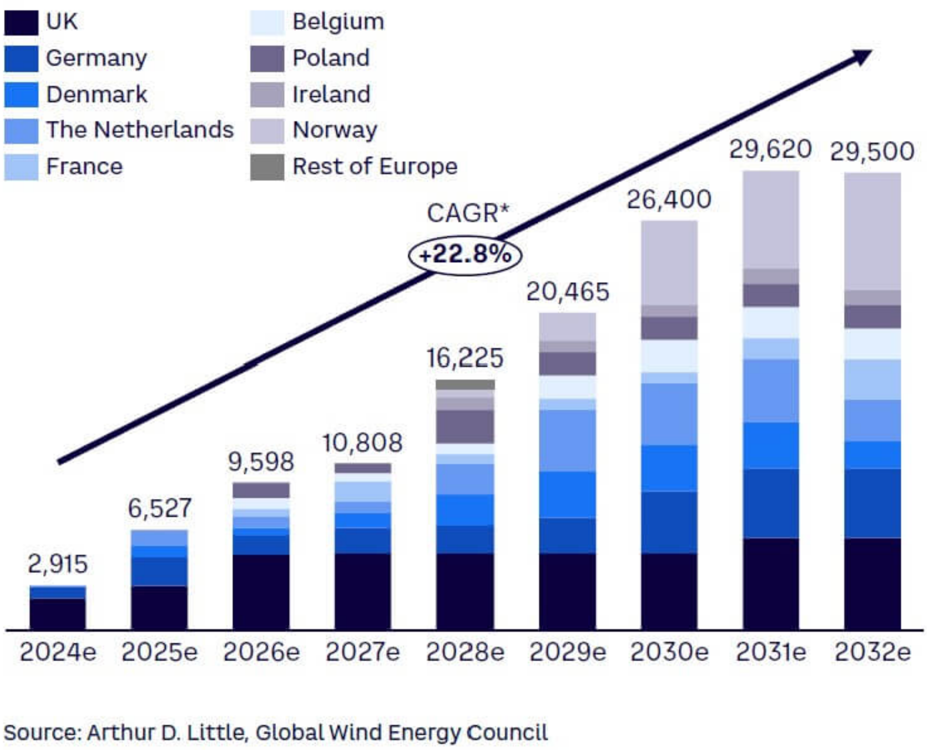

Figure 1.1: Expected offshore wind installation growth in Europe

Sea's vast wind resources places it in a strong position to achieve these goals. The Dutch government aims to increase its offshore wind capacity sixfold, from 3.5 GW in 2021 to 21 GW by 2031(Noordzeeloket, 2025). This requires substantial infrastructure investment to integrate offshore-generated power into onshore grids effectively.

A crucial player in realizing the Netherlands' offshore wind ambitions is TenneT, the Dutch-German TSO. As one of Europe's largest grid operators, TenneT is responsible for balancing short-term energy supply and demand while planning long-term transmission capacity (TenneT, 2023b). The company operates a 25,000 km network, serving 43 million customers across the Netherlands and Germany. Now, in response to the Esbjerg Declaration to facilitate the large-scale integration of offshore wind energy, TenneT has developed the 2GW Program (Figure 1.2). It is a pioneering initiative designed to accelerate offshore grid expansion using standardized 2 GW HVDC grid connections. By implementing these state-of-the-art transmission systems, the program aims to enhance efficiency, minimize environmental impact, and improve the scalability of offshore wind projects (TenneT, 2023b). The 2GW Program represents a fundamental shift in offshore grid infrastructure. Traditionally, offshore wind energy was transmitted via smaller-scale connections, requiring a larger number of grid connection systems. In contrast, the 2GW Program's standardized HVDC platforms will significantly reduce the number of connection systems required while simultaneously increasing total transmission capacity (TenneT, 2025). The program is expected to deliver 14 offshore grid connections by 2032 of which six are in Germany and eight in the Netherlands, each with a 2 GW capacity, collectively providing 28 GW of transmission capacity (TenneT, 2023b).The construction of the 2GW Program presents significant engineering challenges. Integrating offshore wind energy into national grids demands use of advance methodologies and practices to ensure smooth execution, scalability, and reliability. Current project management (PM) practices often fall short in managing such complexity, highlighting the need for SE.

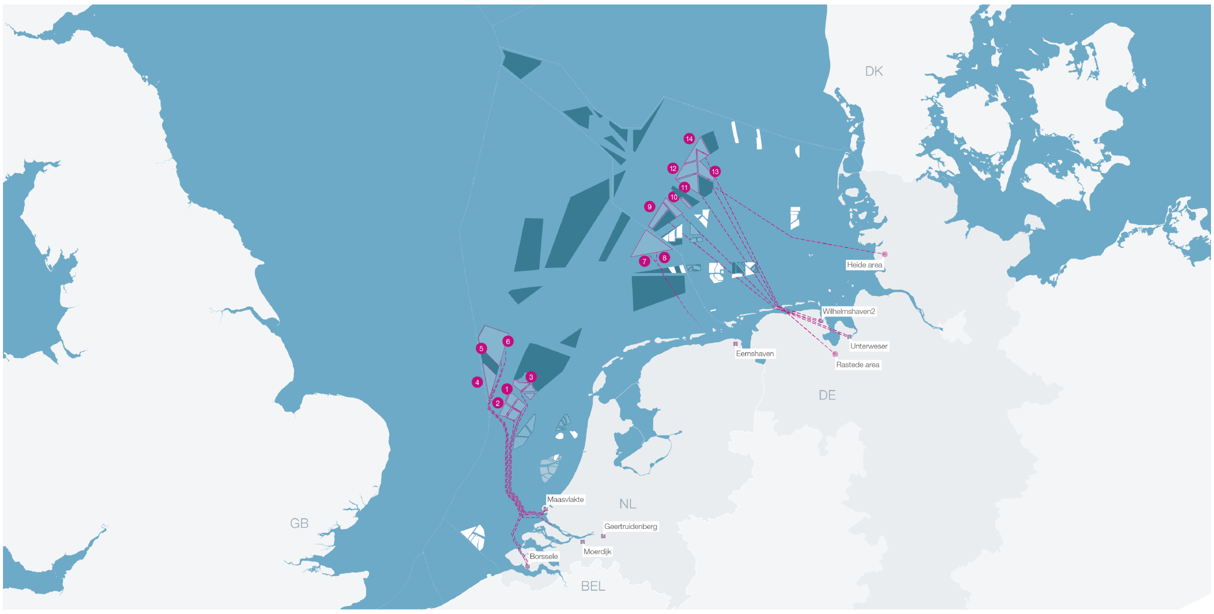

Figure 1.2: Locations of the 2GW Program. In the Nederlands: IJmuiden Ver Alpa/Beta/Gamma, Nederwiek 1/2/3, Doordewind 1/2. In Germany: BalWin 3/4, LanWin 1/2/4/5

As defined by International Council on Systems Engineering (INCOSE) (2023): "Systems Engineering is a transdisciplinary and integrative approach to enable the successful realization, use, and retirement of engineered systems, using systems principles and concepts, and scientific, technological, and management methods". This approach is guided by ISO 15288 standards and the INCOSE SE Handbook. These frameworks emphasize early-stage modeling and peer reviews to reduce design flaws and integration risks. However, the practical application of SE frequently diverges from its theoretical ideals. Many SE work products, developed early in the project lifecycle, reveal their limitations only during later stages of execution. This raises critical questions about the tangible benefits of adopting SE practices, the challenges encountered during implementation, and the strategic recommendations necessary for organizations aiming to apply SE in large infrastructure projects like the 2GW Program. As construction is still underway, the full extent of SE's impact remains to be seen, making it essential to explore what steps TenneT can take to continuously realize these benefits.

Accordingly, this research aims to evaluate the role of SE in large-scale offshore grid connection initiatives, with the 2GW Program serving as a case study. The study focuses on identifying the program's initial goals, examining the current implementation of SE practices, and assessing the benefits they are expected to deliver. Ultimately, this thesis seeks to provide actionable recommendations and strategic insights to enhance and sustain the value of SE in complex infrastructure projects.

2

Defining the Research Gap

The increasing complexity of civil engineering projects, along with growing expectations for economic, safe, and sustainable infrastructure, demands a more systematic approach to project execution (ProRail et al., 2013). Large-scale developments often involve multiple stakeholders, making coordination, efficiency, and performance optimization essential. In recent years, advances in technology, the rise of standardization, and structured methodologies have improved project outcomes. Among these, SE has gained recognition for its potential to manage complexity and enhance project performance. TenneT, one of Europe's major TSOs, has positioned itself at the forefront of SE implementation in offshore grid expansion initiatives. Responsible for maintaining over 25,000 kilometers of high-voltage infrastructure across the Netherlands and Germany, TenneT plays a pivotal role in ensuring a reliable energy supply (TenneT, 2024). To meet the rising demand for offshore wind integration and contribute to European energy transition goals, TenneT has launched the 2GW Program, aiming to develop fourteen HVDC offshore grid connections by 2031 (Van de Werke, 2024).

Previous studies, such as that by (E. C. Honour, 2004), have underscored the critical role of SE in project success. The research shows that projects investing 15 to 20% of their resources in SE practices experience significantly improved cost and schedule control, while projects lacking SE face frequent overruns and misaligned requirements. SE enables a structured, traceable framework for requirement definition, process optimization, and project controllability - attributes increasingly valued in civil infrastructure (ProRail et al., 2013). Within the 2GW Program, SE principles are now being employed to promote harmonization, reduce inefficiencies, and enable long-term cost savings (TenneT, 2023a). These principles include establishing a requirement database, collaborating with HVDC suppliers through a proof-of-concept approach, and applying a "first-time-right" strategy under contractual structures such as FIDIC (TenneT, 2025).

However, a notable research gap persists: there is limited empirical understanding of the specific benefits SE brings to offshore grid connection projects, and the conditions under which these benefits materialize remain unclear (Rooijen, 2008). Although broader systems approaches such as systems thinking, complexity theory, and cognitive complexity have been proposed to manage large-scale projects (Findlay & Straus, 2011), their integration into SE evaluation frameworks has not been widely explored. Also, the absence of standardized methods for assessing SE effectiveness complicates efforts to quantify its impact. Further, E. C. Honour and Valerdi (2006) found that SE effort distribution varies significantly across lifecycle phases and organizations, with large standard deviations reflecting inconsistent application. These variations become more pronounced in the construction sector, where project phases are often distributed between clients and contractors. Consequently, many project employees may struggle to recognize the value SE provides. Van den Houdt and Vrancken (2009) emphasized the need for further research into how project staff perceive SE benefits and the usability of its tools, suggesting that better understanding could enhance perceived value and adoption.

To address this gap, this thesis explores the implementation of SE in offshore grid connection projects from the client's perspective, focusing on the TenneT 2GW Program. By doing so, it aims to identify concrete benefits, challenges, and recommendations for optimizing SE use in complex infrastructure programs. Closing this gap is essential to ensure SE practices deliver measurable outcomes, strengthen stakeholder alignment, and improve overall project delivery in the civil engineering domain.

3

Research Outline

This chapter outlines the core components of the research, beginning with the main research question and accompanying subquestions that guide the study. It then presents the research methodology used to explore the role and value of SE within the 2GW Program. By combining theoretical evidence for understanding the depth of the problem and using insights from a real-world case study of an offshore grid connection program, this research aims to provide actionable insights for both practitioners and researchers engaged in SE implementation in the infrastructure industry.

3.1 Research question

The earlier discussion highlights that while SE has been systematically integrated into the 2GW Program, its tangible benefits and operational effectiveness have yet to be fully realized, necessitating an assessment and continuous refinement. This research aims to analyze the efficiency of applying SE within an offshore grid connection program. To do this, the principal research question is formed as:

> *"How can the application of Systems Engineering (SE) address the challenges in offshore grid connection projects and maximize long-term benefits for Transmission System Operators (TSOs)?"*

To comprehensively address this inquiry, the following subquestions will be explored:

- What were the key challenges and problems faced in offshore grid connection projects that necessitate the application of SE?
- What are the expected benefits of SE implementation for TSOs, particularly in the context of offshore grid connection programs?
- How have the anticipated benefits of SE been realized in the case study, and what strategies can enhance and sustain these benefits in the future?

3.2 Research Methodology

This study employs a qualitative research methodology to explore the role of SE in offshore wind infrastructure projects. To determine the value of SE, the idea is to evaluate the 2GW Program by following the framework proposed by Weiss (1972). This evaluation will begin with identifying the rationale behind the program, ensuring a clear understanding of the underlying motivations for its implementation. Following this, specific program goals will be established that define the intended outcomes of SE within the offshore grid expansion initiative. Once these objectives are set, we will assess the current status of expected benefits. Finally, the collected data will be systematically analyzed to derive insights into the effectiveness and impact of SE in the 2GW Program. The comprehensive methodology is detailed in Figure 3.1.

The research began with an extensive literature review to understand the theoretical background of SE and its application in large infrastructure projects. A literature review is a structured way of identifying, evaluating, and synthesizing existing research, which helps in building a knowledge base and guiding further inquiry (Baumeister & Leary, 1997). A well-conducted review is essential for developing a conceptual framework and generating meaningful research questions (Webster & Watson, 2002). The literature study formed the theoretical basis of understanding the clear problems that necessiate the use of SE principles. An exploratory case study was conducted to examine how SE is applied in practice within the context of offshore wind infrastructure, specifically the 2GW Program. As noted by Yin (2009), exploratory case studies are effective when the research topic is not clearly defined and requires in-depth empirical investigation. Given the complexity and evolving nature of offshore grid projects, the case study design provided valuable insights into stakeholder perspectives, implementation challenges, and emerging benefits of SE in a real-world setting.

To support the case study, a structured document analysis was carried out. This method involved reviewing internal reports, correspondence, and other project-related materials such as program charter, SE guideline for the 2GW, etc to gather contextual information and track developments over time (Bowen, 2009). Document analysis is particularly useful in qualitative case studies because it offers rich background data and helps validate findings obtained through other methods. It also aids in identifying key changes, decisions, and issues that arose during the course of the project (Yin, 2009). This method contributed significantly to understanding how SE practices were implemented and adapted throughout the project lifecycle and what the possible implications of perceived SE benefits are over the course of a program. Then, to gather firsthand insights and perspectives from stakeholders, semi-structured interviews were conducted. This format provided a balance between predefined questions and the flexibility to explore emerging themes (Alsaawi, 2014). The interviews helped clarify stakeholder experiences and perceptions of SE, including its perceived benefits and ongoing challenges. To further strengthen the credibility of the findings, member checking was applied. This process involved sharing key interpretations with selected participants to confirm the accuracy of the conclusions (Russell & Gregory, 2003).

Each method contributed to different aspects of the research, supporting a comprehensive understanding of the problem and enabling triangulation of findings. The first sub-research question, which deals with identifying key challenges in offshore grid projects, was addressed using insights from both the literature review (Sections 4.1 & 4.2) and the interviews (Section 9.1). The second sub-research question, concerning how SE is implemented and what benefits it brings, was explored through the case study, supported by literature study (Section 4.3), document analysis (Chapters 6 & 7) and interviews (Section 9.2). Finally, the third sub-research question, which focuses on evaluating benefits and proposing improvements, was answered by comparing the findings from the literature(Section 5) and the interviews (Sections 9.2 & 9.3) to identify gaps and opportunities for improvement.

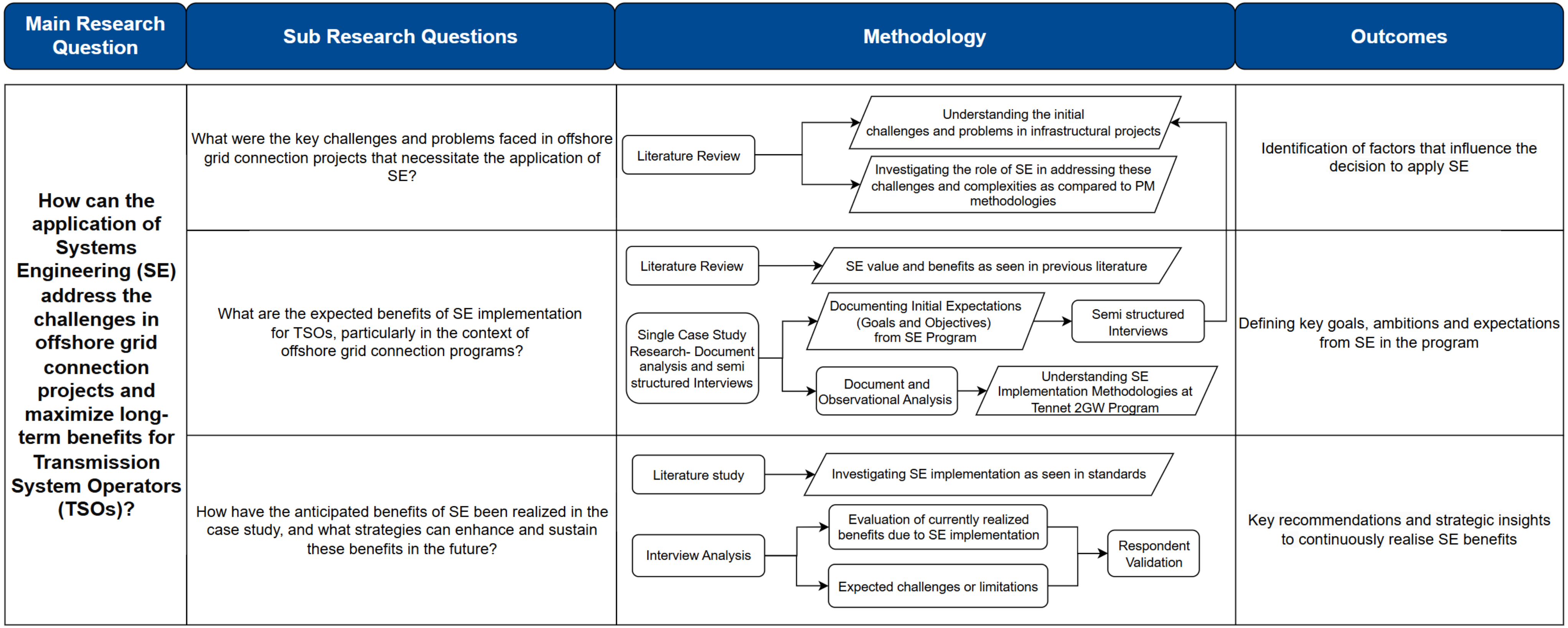

Figure 3.1: Research Methodology

4

Literature Review

In recent years, support for and the application of SE has increased to deal with such complexities and uncertainties in projects. Organizations are increasingly recognizing SE as a means to enhance project controllability and efficiency, allowing for better project setup and execution. Nonetheless, the introduction of SE remains a challenging process, as its implementation requires overcoming various organizational and technical hurdles (ProRail et al., 2013). The offshore industry, in particular, has yet to fully embrace SE principles and continues to rely on conventional PM methods. TenneT has initiated a pivotal step towards integrating SE into offshore PM through its 2GW Program.

So to gain a deeper understanding of the theoretical background and current developments, a comprehensive literature review was conducted. Academic sources were identified using multiple databases including Web of Science, Scopus, Google Scholar, and the American Society of Civil Engineers Library. Additional searches were performed in Wiley Online Library, Taylor & Francis, Emerald, and ScienceDirect. The goal at this stage was to provide a broad overview of the research problem and assess the current state of knowledge on the topic. This aligns with the purpose of an integrative review, which aims to explore the knowledge base, critically analyze existing studies, and contribute to the theoretical development of the subject (Snyder, 2019).

The literature review was carried out in stages throughout the research process. In the initial phase, searches were conducted using combinations of keywords such as "OFFSHORE", "CONSTRUCTION", "ISSUES", "PROBLEMS", "NEED", "REQUIREMENT", "SYSTEMS", "SYSTEMS ENGINEERING","COMPLEXITY", "PPT framework", "People" and "Processes". Boolean operators (AND, OR, NOT) were used to refine the search and focus on relevant publications. Secondary sources were also identified by examining reference lists to broaden the scope and include related issues that highlight the need for transitioning from traditional PM methods to SE. For the latter part of the review, additional sources were gathered from publications such as the SE journal, the SE Body of Knowledge (SEBoK), SE guidelines for the Dutch industry, and proceedings from the INCOSE International Symposium. These were supplemented with secondary sources and reference tracing to identify research with strong relevance to SE value and benefits. The SE processes reviewed in the second stage were refined to focus on the key themes that were developed during the interview phase.

This chapter proceeds by first exploring the challenges faced in the offshore sector that necessitate the adoption of SE, particularly in the context of offshore grid connection projects. It then presents an overview of the benefits of SE as reported in academic and industry literature, followed by a review of SE implementation practices based on existing standards and frameworks.

4.1 Investigating the need for SE

To develop an effective system, the first critical step is to understand the needs of all stakeholders. This entails identifying and engaging both internal and external stakeholders early in the process (Makolm, 2006). Aligning these needs with core business processes is vital for translating them into actionable software or system requirements. However, a common shortfall in large infrastructure lies in the disconnection between the systems delivered and the actual processes as perceived by end users (Makolm, 2006). Often, this misalignment stems from traditional project tracking methods that overlook stakeholder dynamics and business process integration. To address this gap, we adopt the People-Process-Technology (PPT) framework, which serves as a tool to evaluate issues in current offshore grid project scenarios from these three perspectives that inform the use of SE.

Efficient processes alone are insufficient without the right people-those equipped with the necessary skills, practices, and organizational fit to implement them. Therefore, successful delivery depends on aligning the capabilities of individuals with well-designed processes that reflect stakeholder needs. In turn, the appropriate tools and technologies must empower these individuals to operate effectively and innovate within their domains (Haron et al., 2013). Although widely applied, the conceptual origins of the PPT model can be traced back to Leavitt's Diamond model (Leavitt et al., 1964), which emphasized interdependence among organizational components. This model of PPT continues to inform modern organizational strategies and system development approaches, particularly in contexts requiring tight integration and transformation (Mêda et al., 2020; Owen et al., 2013).

Accordingly, this study uses the PPT lens (Figure 4.1) to identify the underlying issues necessitating a SE approach in large, collaborative programs like TenneT's 2GW offshore grid expansion. Together, these insights will form the foundation for motivating the adoption of a SE approach to improve governance, integration, and execution in high-stakes infrastructure programs.

Figure 4.1: People-Process-Technology Dimensions

4.1.1 People Related Issues

Offshore and construction projects are inherently very complex and are influenced by interactions among diverse stakeholder groups. The effective alignment of stakeholder interests, communication clarity, resource management, and standardized execution are critical factors that can impact the success of offshore grid connection projects. Project environments in construction are considered complex if they involve multiple distinct disciplines, methods, or conflicting stakeholder requirements (Locatelli et al., 2014). Each project presents unique challenges that are difficult to predict, demanding meticulous management to avoid significant cost and time overruns. Managing construction teams, often assembled ad hoc and changing frequently from project to project, poses additional complexities (Emes et al., 2012). Stakeholders typically include government entities, private investors, environmental advocates, local communities, and technical specialists, each contributing unique and often conflicting requirements, priorities and concerns (Hubert, 2021). Projects have many stakeholder conflicts, making alignment among diverse groups a challenge. For example, Investor interests usually revolve around profitability and cost-efficiency, whereas environmental organizations prioritize rigorous ecological protection measures. Local communities frequently raise concerns related to disruptions in their livelihoods or environmental impacts. Concurrently, regulatory bodies enforce stringent compliance measures, which, if not addressed early in the planning stages, may significantly delay project timelines (Engle & van Senten, 2022). Investors' emphasis on financial performance and profitability further intensifies tensions with environmental groups insisting on strict ecological compliance, and regulatory frameworks compound these tensions by introducing additional costs and potentially extending project timelines (Alex, 2023; Wiegner et al., 2024).

Operational divergences among contractors and technical specialists also contribute significantly to the complexity of construction and offshore projects. Conflicting technical priorities among these groups often complicate consensus-building processes. Communication barriers further amplify these issues, as stakeholders tend to operate in isolated silos, leading to misunderstandings and misalignment of objectives. Such misalignments may escalate into broader disputes, resulting in project delays, increased costs, and even risks to overall project viability. Technical teams, for example, may design project components without adequately considering regulatory requirements, necessitating costly revisions and subsequent delays (Adewoyin et al., 2025). Furthermore, language barriers and extensive technical jargon hinder stakeholder engagement, especially in international projects involving diverse technical expertise. Effective communication is paramount in aligning diverse stakeholder interests yet remains a critical vulnerability in energy projects (ProRail et al., 2013).

Moreover, customer dissatisfaction in the construction industry typically arises from failures in accurately understanding and translating customer requirements into practical and deliverable solutions (Dulami et al., 2012). The lack of clear stakeholder feedback channels exacerbates these communication gaps, delaying decision-making and undermining confidence among stakeholders (Adewoyin et al., 2025). The project-based nature of construction often leads to inconsistent solutions for similar customer needs, significantly limiting organizational learning opportunities and hindering process standardization. High-value offshore projects, involving substantial financial investments from key stakeholders, particularly exacerbate these pressures. Such projects frequently face intense demands to deliver high-quality results within strict budgetary and time constraints. Additionally, these projects must manage considerable stakeholder-driven changes, often introduced mid-project, which further complicate execution. Suppliers must balance conflicting objectives of delivering quality outcomes, adhering to tight budgets, and meeting stringent timelines. Their performance across quality, cost, and timing directly impacts their reputation and future business opportunities (Emes et al., 2012).

Finally, the offshore sector faces a critical shortage of skilled personnel, significantly affecting its capacity to scale production and installations effectively. As projects become increasingly large and complex, precise resource management becomes essential to avoid resource shortages and optimize utilization (ProRail et al., 2013). Integrated strategies for resource allocation are hence very critical, enabling effective management of manpower, equipment, and materials amid rapidly evolving project demands (Wu et al., 2024).

Table 4.1: People-Related Issues Necessitating SE

Issue Category	Identified Problems	Citations
Stakeholder Management	• Conflicting stakeholder requirements and many interfaces. • Frequent and unpredictable requirement changes. • Need for flexibility balancing quality, schedule, budget. • Lack of common language and integrated processes. • Fragmented teams hindering transparency and accountability. • Difficulty integrating stakeholder and client needs.	Locatelli et al. (2014), Emes et al. (2012), Hubert (2021), Adewoyin et al. (2025), Dulami et al. (2012)
Skill and Resource Availability	• Scarcity of qualified personnel for scaling up. • High resource utilization due to project scale.	ProRail et al. (2013), Wu et al. (2024)

4.1.2 Process Related Issues

Offshore energy projects such as the 2GW Program face several challenges across process-related fields, including lifecycle management, risk, regulation, finance, and procurement. Construction project lifecycles traditionally follow a sequential process with limited overlap between stages, reducing the opportunity for iterative improvements. The lack of early prototyping and testing restricts feedback on the end product's alignment with customer expectations, making it challenging to address major deficiencies economically once construction has started (Emes et al., 2012). Further adding to the issue, the final constructed system often diverges from initial designs, and deficiencies discovered during subsystem testing can reveal critical flaws in overall architectural designs (Martin, 2004).

Risk and opportunity management pose another critical challenge. The highest uncertainty levels are typically experienced in the initial project stages, where early decisions disproportionately impact project costs and duration (Godfrey, 1996). Changes, inevitable in large-scale capital projects, are frequently underestimated during early phases, compounding the project's risk profile (Mills, 2001). , Further market inefficiencies and knowledge asymmetries during contract negotiations, combined with rigid contract structures, further complicate risk management (Barlow, 2000). Traditional tendering processes, conducted on a project-by-project basis, have historically been inefficient. So large-scale tenders and bundled contracts are now introduced to increase predictability, they also introduced significant financial risks due to suppliers' reluctance to engage in expensive and complex tendering processes with uncertain financial returns (Locatelli et al., 2014). While these improve predictability,The size and long duration (10–14 years) of contracts introduce financial risks for both TenneT and its suppliers. Suppliers must secure financing and guarantees for large-scale orders, which can be a barrier. Uncertainties in energy policies and fluctuating market conditions create additional financial risks (Little, 2024).

Navigating the regulatory landscape is a critical challenge for offshore energy projects, particularly due to the complexities of operating across multiple jurisdictions. Variations in compliance requirements often result in bureaucratic delays, impacting project timelines significantly. Achieving regulatory synergy, which entails harmonizing compliance across regions, is essential for expediting project execution(Afolabi et al., 2024). Offshore wind cable routes that traverse environmentally sensitive areas further complicate the permitting processes, thereby introducing uncertainties and delays (Locatelli et al., 2014). Moreover, regulatory rigidity can be counterproductive, especially for integrated offshore grids, as rigid rules may discourage long-term planning and economic incentives (Dedecca et al., 2019).

Offshore projects further demand extensive use of partners' tangible and intangible resources, highlighting their strategic significance (Locatelli et al., 2014). Europe's rapid energy transition necessitates scaling up offshore wind energy infrastructures swiftly, with numerous projects concurrently targeting completion by 2030 (Cusumano et al., 2024). This compressed timeline increases execution pressures significantly. Although bundling projects into large contracts enhances efficiency, it concurrently restricts competition by limiting market entry, thus creating dependencies on a few suppliers and increasing mutual risk exposure. Achieving an optimal balance between maintaining a competitive supplier base and fostering long-term collaboration presents complex strategic challenges (Locatelli et al., 2014).

Table 4.2: Process-Related Issues Necessitating SE

Issue Category	**Identified Problems**	**Citations**
Regulatory & Permitting	• Multi-agency approvals causing delays. • Complex ecological and regulatory processes increasing uncertainty.	Little (2024)
Lifecycle Management	• Sequential lifecycle limiting early feedback and prototyping. • Limited subsystem testing leads to late-stage design issues. • Inadequate lifecycle consideration restricts innovation.	Emes et al. (2012), Martin (2004), Beasley (2017)
Risk & Opportunity Management	• Limited early identification and management of risks. • Inadequate handling of uncertainties and assumptions.	Godfrey (1996) Mills (2001)
Financial & Procurement Processes	• Financial risks from large, long-term contracts. • Unpredictable tendering leading to supplier hesitation. • Balancing competition with stable collaboration is complex.	Little (2024)
Industry Fragmentation	• Fragmented design/production reduces transparency. • Hinders timely, budget-conscious delivery.	Cusumano et al. (2024), Emes et al. (2012)

4.1.3 Technology Related Issues

The construction industry is widely recognized for its high fragmentation in both design and production processes. This fragmentation results in challenges related to transparency and the clear allocation of responsibility, stemming from many interfaces between project elements and organizational entities (Locatelli et al., 2014). According to Mohd Nawi et al. (2014), fragmentation in construction can manifest in multiple forms: project fragmentation, characterized by independent handling of project phases such as design and construction; industry fragmentation, which involves the isolated operations of entities like contractors and suppliers; team fragmentation, where specialists such as architects and engineers operate separately within teams; and supply chain fragmentation, marked by inadequate communication and coordination among clients, contractors, and subcontractors. These fragmentation forms collectively contribute to inefficiencies and hinder the successful integration of project components.

Managers in construction should adopt a systems perspective, as highlighted by (Emes et al., 2012), to better understand and manage the stakeholder requirements of the constructed system and its subsystem interfaces. Enhanced understanding of these interfaces enables concurrent engineering, facilitating overlapping activities across project lifecycle stages, thus mitigating the issue of subsystem validation, which traditionally cannot occur until project completion. Specifically for TSOs, recent studies by (Little, 2024) highlight additional technological and market challenges. Offshore wind projects frequently utilize AC transmission technology, which is inefficient for long-distance transmission, necessitating a shift toward HVDC systems. However, the implementation of advanced HVDC systems, particularly those rated at 525 kV and 2 GW, remains technically complex due to their evolving nature. Furthermore, the supply chain for HVDC technology is significantly constrained, with only six manufacturers capable of producing 525 kV HVDC cables globally and only three Western manufacturers of HVDC converters. This shortage of critical components, including offshore platforms, cables, installation services, and qualified skilled labor, presents substantial barriers. The demand for offshore HVDC components is projected to surpass available supply as early as 2025/2026, worsening these constraints and further complicating efforts to scale manufacturing and installation capacities across Europe due to a pervasive shortage of qualified personnel.

Table 4.3: Technology-Related Issues Necessitating SE

Issue Category	Identified Problems	Citations
Technological Complexity	• Transition from AC to evolving HVDC (525 kV, 2GW). • Technical challenges in implementing new HVDC systems.	Little (2024)
Supply Chain Constraints	• Limited suppliers for critical HVDC components. • Demand to outstrip supply by 2025/2026. • Shortages in cables, platforms, installation services.	Little (2024)
Innovation & System Integration	• Multiple disciplines and interfaces complicate integration. • Ensuring cohesive innovation across subsystems is difficult.	Locatelli et al. (2014), Mohd Nawi et al. (2014)

4.2 Issues in Existing PM Methodologies

Modern construction projects are increasingly defined by ambitious scopes, larger physical dimensions, and complex structural designs, often incorporating cutting-edge materials. This growing complexity is driven by multiple factors, including the expansion of project scale, the adoption of advanced technologies, and the enforcement of stricter sustainability and CO2 emission regulations (Emes et al., 2012). The traditional PM methodologies, while they are effective under stable conditions, often struggle to cope with the high levels of uncertainty and interdependencies that define modern construction projects. According to Brady and Davies (2014), failure to manage increasing project complexity is a primary reason why many projects fail to meet their cost, schedule, or quality targets. They argue that in an era of rapid change and unpredictability, traditional PM methods are insufficient, and construction projects should instead be viewed as complex adaptive systems. Such systems show path dependencies and high sensitivity to initial conditions, making it difficult to establish regularity, element separability, or clear cause-and-effect relationships.

Construction projects are facing an increase in requirements since the projects are getting larger, more technology is integrated, and new sustainability and CO2e emissions requirements are introduced (Emes et al., 2012). As a result, requirement management quickly gets overwhelming, and instead of having systematic requirement management, the construction industry tends to trust craftsmanship (Aslaksen et al., 2008). In addition, construction projects span long time intervals and often face changes during the project's progress, making requirements traceability even more complex. Building projects are becoming ever more ambitious in terms of physical size, complexity of structures and materials used. Large buildings are increasingly 'intelligent', integrating many technologies such as for security, safety, communications, comfort and entertainment. Furthermore, the number of requirements and the number and influence of stakeholders continues to grow(Emes et al., 2012).

As per (Galli, 2020) there are many shortcomings attributed to traditional PM. Tracking and maintaining a pre-specified duration and budget is one of the most important aspects of PM. In projects today, increased rates of project failure are commonly derived from cost overruns and delays. Also, consistency between tasks and/or whole projects is lacking in projects. It is being shown that the current practices of PM are becoming less able to manage project risks. To deal with the risks associated with increased complexity, a new approach to PM should be taken, as modern projects are growing larger and more complex. Projects are organised on the basis of discipline rather than safeguarding integrated nature of Projects , therefe there is a need of Change from responsibility based thinking to process based thinking (ProRail et al., 2013). The field of PM has the potential to make improvements to its practices. These shortcomings are deeply rooted in traditional PM's inability to effectively address the increasing complexity and interconnected nature of modern infrastructure projects (Brady & Davies, 2014). Such projects frequently feature rapidly changing technologies, shorter technology cycles, and elevated risks of obsolescence (Hanratty et al., 1999). Moreover, the integration challenge intensifies with a growing number of interdependent system parts and involved organizations (Calvano & John, 2004), combining multiple technical disciplines under conditions of intense competitive pressures (Faulconbridge & Ryan, 2005; Kossiakoff et al., 2011).

Furthermore, the consistency between tasks and entire projects remains problematic, reducing reliability and project outcomes (ProRail et al., 2013). Projects are organized along disciplinary lines rather than integrated processes, which often fail to manage complexities effectively, indicating the need for a shift from responsibility-based thinking to process-oriented approaches (ProRail et al., 2013). Traditional PM also suffers from problems in knowledge transfer, exacerbated by short-term and finite project lifecycle perspectives (Galli, 2020).

In recent grid projects, the involvement of multiple stakeholders has grown significantly, adding to the challenges of project governance. The fragmentation of design and production processes further complicates transparency and accountability, making it increasingly difficult to ensure projects are completed on schedule, within budget, and in alignment with client expectations (Cusumano et al., 2024). Stakeholder trust significantly influences project outcomes, especially concerning adherence to project schedules (Chitongo & Pretorius, 2018). Frequent schedule slippages cause stakeholders to lose trust, prompting them to impose extra project controls that further burden PM teams, negatively impacting workforce productivity and overall project progress (Chitongo & Pretorius, 2018).

Current methods function adequately only if projects are simple enough and uncertainties are manageable. However, as complexity and uncertainty intensify, these traditional methods are increasingly inadequate (Rolstadås & Schiefloe, 2017). Offshore grid connection projects such as the 2GW Program can be understood as complex adaptive systems, characterized by path dependencies, sensitivity to initial conditions, and nonlinear interactions (Brady & Davies, 2014). Therefore, assumptions of regularity, separability, and clear cause-and-effect relationships typical in traditional PM practices do not hold.

The above findings have been summarized in table 4.4

Table 4.4: Problems in Current PM Approaches

Category	**Identified Issues**	**Citations**
Complexity Management	• Traditional methodologies fail to manage increased complexity and interdependencies. • Path dependencies and high sensitivity to initial conditions not effectively handled. • Difficulty ensuring regularity, separability, and clear cause–effect relationships.	Brady and Davies (2014), Rolstadås and Schiefloe (2017)

Continued on next page

Table 4.4 continued

Problem Category	Identified Issues	Citations
Requirement Management	• Overwhelming increase in project requirements due to scale, technological integration, and new sustainability regulations. • Reliance on craftsmanship rather than systematic requirement management. • Poor traceability and management of evolving requirements during project lifecycle.	Emes et al. (2012), Aslaksen et al. (2008)
Stakeholder Management & Governance	• Increased number and influence of stakeholders, leading to challenges in governance. • Fragmented design and production processes reducing transparency and accountability. • Stakeholders impose increased controls due to lack of trust, reducing PM productivity.	Cusumano et al. (2024), Galli (2020), Chitongo and Pretorius (2018)
Risk & Uncertainty Management	• Inadequate management of risks associated with rapid technological changes and high uncertainty. • Current approaches insufficiently flexible to respond effectively to unforeseen changes.	Brady and Davies (2014), Rolstadås and Schiefloe (2017), Galli (2020)
Integration & Coordination	• Projects organized by discipline rather than integrated processes, causing coordination issues. • High interoperability and interdependence creating integration challenges across multiple disciplines and organizations. • Short-term focus leads to poor long-term knowledge transfer and reduced integration effectiveness.	ProRail et al. (2013), Locatelli et al. (2014), Faulconbridge and Ryan (2005), Calvano and John (2004)
Cost, Time, and Quality Control	• Frequent failures in maintaining budgets and timelines, leading to delays and cost overruns. • Pressure for cost reduction and accelerated schedules causing quality compromises. • Inconsistencies in task execution, affecting overall project outcomes.	Galli (2020), Laufer et al. (1996), Locatelli et al. (2014)
Information Management Issues	• Poor communication of information between project teams and stakeholders significantly undermining project success. • Lack of effective project knowledge transfer mechanisms, particularly in complex and large-scale projects.	Galli (2020), Chitongo and Pretorius (2018),

4.3 Understanding SE approach and and its Benefits

INCOSE (2010) explains "SE is an integrative approach to help teams collaborate to understand and manage systems and their complexity and deliver successful systems. The SE perspective is based on systems thinking - a perspective that sharpens our awareness of wholes and how the parts within those wholes interrelate. SE aims to ensure the pieces work together to achieve the objectives of the whole. SE practitioners work within a project team and take a holistic, balanced, life cycle approach to support the successful completion of system projects". However, a truly successful system is one that not only fulfills the needs and expectations of its users and other stakeholders, but also sustains high levels of operational efficiency over its entire life-cycle. SE provides the structured, interdisciplinary approach required to achieve this balance. As Kossiakoff et al. (2011) stresses, SE keeps a system aligned with its design intent while ensuring it can adapt gracefully as requirements, technologies, and external conditions evolve. According to (Kossiakoff et al., 2011), SE way of working can be understood through various process models (Figure 4.2) that depict the sequence of design, development, integration, and testing. These models have evolved from simple linear processes to more iterative frameworks. Early graphics illustrated a linear sequence of steps, often iterative, to maintain consistency and viability. The waterfall model follows a strict sequential flow, while spiral models integrate iterative loops to manage evolving requirements and risks.

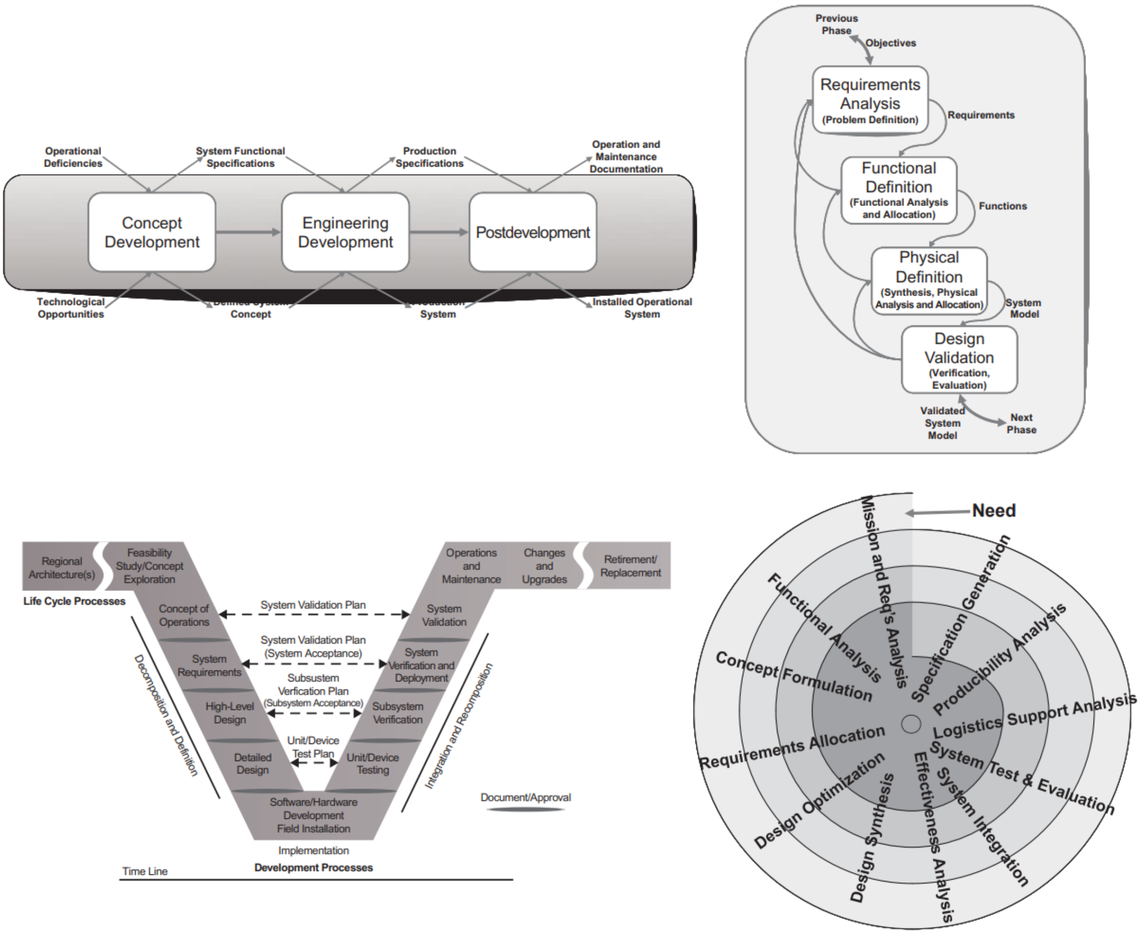

Figure 4.2: Examples of SE approaches by Kossiakoff et al. (2011)

The value delivered by SE can be viewed from several complementary angles as discussed by (B. J. Elliott, 2014). One perspective emphasises “better systems,” in other words solutions that work reliably, satisfy performance targets, and are resilient to future change. A second perspective highlights “better projects” - those delivered more quickly and at lower cost through disciplined processes and early risk reduction. A third, equally important view recognises that organisations rarely control every project outcome; therefore, simply reducing the variability in cost, schedule, or quality can constitute a significant benefit, even if average performance remains unchanged.

Although the literature offers limited discussion on the ’benefits of SE’, this review seeks to explore and interpret the existing research on SE’s value and advantages. It is organized around four key themes that represent the most commonly cited benefits of adopting an SE approach. The first three themes primarily draw from studies that quantify project-level outcomes, while the fourth theme is based on empirical evidence from the Dutch infrastructure sector, highlighting lessons learned from real-world practice.

4.3.1 Controlling Complexity

Once a system crosses a certain threshold of technical, organisational, or stakeholder complexity, attempting to deliver it without a formal SE framework almost inevitably leads to excessive rework and cost overruns (C. Elliott & Deasley, 2007). Modern infrastructure projects illustrate this point vividly: their widening scope, dense stakeholder networks, and tight inter-dependencies are now a primary cause of schedule slippage and failure, as discussed in Section 4.2. Recognizing this, the American Society of Civil Engineers urges that critical infrastructure be "planned, funded, designed, constructed, and operated as a system" integrated with all other interdependent systems (Committee, 2009). Similar conclusions are echoed by McNulty (2011), who list systems approaches among the most effective routes to better value for money.

4.3.2 System-Level Optimization

SE uniquely enables optimization across the entire system boundary, rather than maximizing individual components at the expense of overall performance. Hitchins (1998) argues that focusing narrowly on subsystem metrics invariably undermines the value of the complete system; instead, SE supplies the holistic mechanisms needed to identify the best aggregate solution. Flyvbjerg et al. (2003) analysis of mega projects endorses this approach through the use of "performance specifications," which specify required outcomes rather than prescribing specific designs-thereby granting suppliers the freedom to optimize solutions end-to-end. In the Netherlands, this philosophy underpins recent infrastructure reforms: ProRail and Rijkswaterstaat have shifted design responsibility to the private sector and are actively promoting SE to "focus solutions on maximizing performance and quality" (ProRail et al., 2013).

4.3.3 The "Left Shift"

The "left-shift" hypothesis posits that investing effort-especially SE effort-early in the life cycle yields downstream savings that far outweigh the initial cost. Honour (E. Honour, 2010) captures the orthodox view: systems thinking front-loads requirements analysis, architecture, and trade studies so that integration and testing proceed more rapidly with fewer surprises. The INCOSE (2010) cost-commitment curve reinforces this logic, showing that while expenditures peak late in a project, cost-driving decisions peak early; eliminating errors at that stage is dramatically cheaper. Krueger quantifies the point: by the time 20 % of a project's actual costs have been spent, roughly 80 % of its life-cycle costs are already locked in (Krueger et al., 2011). Yet left-shifting can meet resistance. Project managers may have little incentive to invest in rigorous early-phase analysis when competitive bidding rewards optimistic estimates, and once large projects launch, political or contractual momentum often precludes cancellation despite escalating costs (Emes, 2007; Emes et al., 2012). Overcoming these barriers is therefore crucial to realising the full economic benefit of SE's early-investment philosophy.

4.3.4 Empirical Insights and Practice-Based Themes

From various studies and practical guidelines, especially in the context of Dutch infrastructure projects, several empirical insights and practice-based perspectives highlight the benefits of SE:

1. **Risk Reduction and Minimization of Rework**

   SE significantly reduces the necessity for rework by promoting a "first-time-right" approach, ensuring clarity from the project's beginning and preventing costly modifications at later stages (Ark, 2011). This is supported by SEBoK (2024), emphasizing how early investments in detailed requirement analyses substantially decrease project risks and long-term costs through accurate initial integration.

2. **Enhanced Transparency**

   Transparency is an inherent benefit of SE, enhancing traceability of decisions and financial accountability across the project lifecycle. Explicit documentation ensures that dispersed project teams maintain a unified understanding and effectively manage evolving project phases (ProRail et al., 2013).

3. **Optimized Stakeholder Collaboration and Communication**

   Effective stakeholder management through standardized conceptual frameworks and explicit communication practices is central to SE. Early analysis of stakeholder requirements identifies potential issues promptly, preventing expensive escalations of mistakes in subsequent project phases (ProRail et al., 2013).

4. **Strategic Early-Stage Investment**

   Investing in detailed planning and analysis at the project's early stages is a core principle of SE, consistently shown to deliver significant advantages later in the project's lifecycle, including reduced risk and streamlined dependency management (SEBoK, 2024).

5. **Flexibility and Market Innovation**

   SE encourages flexibility and innovation, particularly in procurement. By avoiding overly detailed specifications, SE principles enable contractors to utilize their market expertise and creativity, enhancing innovation and cost-effectiveness (Ark, 2011). The development of targeted, yet sufficiently open requirement specifications facilitates beneficial market-driven innovations and practical solutions.

6. **System-of-Interest Thinking**

   Utilizing a shared conceptual model, known as the "system-of-interest," SE helps establish consensus on project scope and external interfaces among diverse stakeholders. Context diagrams provided through SE practices facilitate structured and clear identification of interfaces and clarify the project's boundaries (Ark, 2011).

5

SE implementation as per international standards

A number of standards have been developed to guide the implementation of SE in an organization. Standards such as ISO 15288, INCOSE Book, SE Bok of Knowledge, etc, guide the process standards, elaborate on the activities and practices necessary to execute the process. These serve as a reference to practice and methods that have been proven useful to the SE community at large and that can add significant value in new domains such as the offshore grid projects if appropriately selected, tailored, and applied. The idea is to adapt the processes to ensure that they meet the needs of an organization or a project while being scaled to the level of rigor that allows the system life cycle activities to be performed with an acceptable level of risk. In general, all system life cycle processes can be applied during all stages of the system life cycle; tailoring determines the process level that applies to each stage. Additionally, processes are applied iteratively, recursively, and concurrently. While these standards are written for more general activities, for a more focused view on the construction guidelines developed by the Dutch industry, ProRail et al. (2013) is useful. In the construction of an offshore project, since different parties work, such as the client, the contractor, and subcontractors, it is important to pay attention to key processes that are associated, i.e, the responsibilities in the field of V&V activities, and that the arrangements about who validates and verifies what are clear. Roughly speaking, the client is responsible before the transfer, and the contractor is responsible after the transfer. However, the development of the system is independent of the transfer. There are various processes described by these guidelines; however, to focus from a client perspective, it is better to look more closely at three key concepts (result of interview analysis) , i.e., Requirement Management, V&V, and the other supporting and related processes.

5.1 Requirement Management

The development of a system begins with defining customer requirements through a structured approach. The Stakeholder Needs and Requirements Definition process as explained by ISO/IEC (2015) explicitly addresses stakeholder identification and analysis throughout the system's lifecycle. It consolidates stakeholder needs into a common set of stakeholder requirements, describing intended system interactions with its operational environment. These requirements form the benchmark against which the system's capabilities are validated, considering interactions with other interoperable and enabling systems. Subsequently, the System Requirements Definition process as seen by ISO/IEC (2015), converts these stakeholder-focused requirements into technical, measurable system requirements. This step specifies the necessary characteristics, functions, attributes, and performance parameters the system must possess to satisfy stakeholder expectations. Notably, this specification avoids prescribing particular implementations, subject to existing constraints.

Stakeholder identification and engagement are critical, ensuring perspectives from every lifecycle phase are considered.Further, Customer requirements often include preconditions such as time and budget constraints. Proactive analysis of these requirements helps identify potential conflicts or unrealistic expectations early in the process, facilitating informed decisions about acceptance or adjustments. These decisions, agreed upon in collaboration with customers at project or higher levels, are formally documented in a CRS (ProRail et al., 2013)

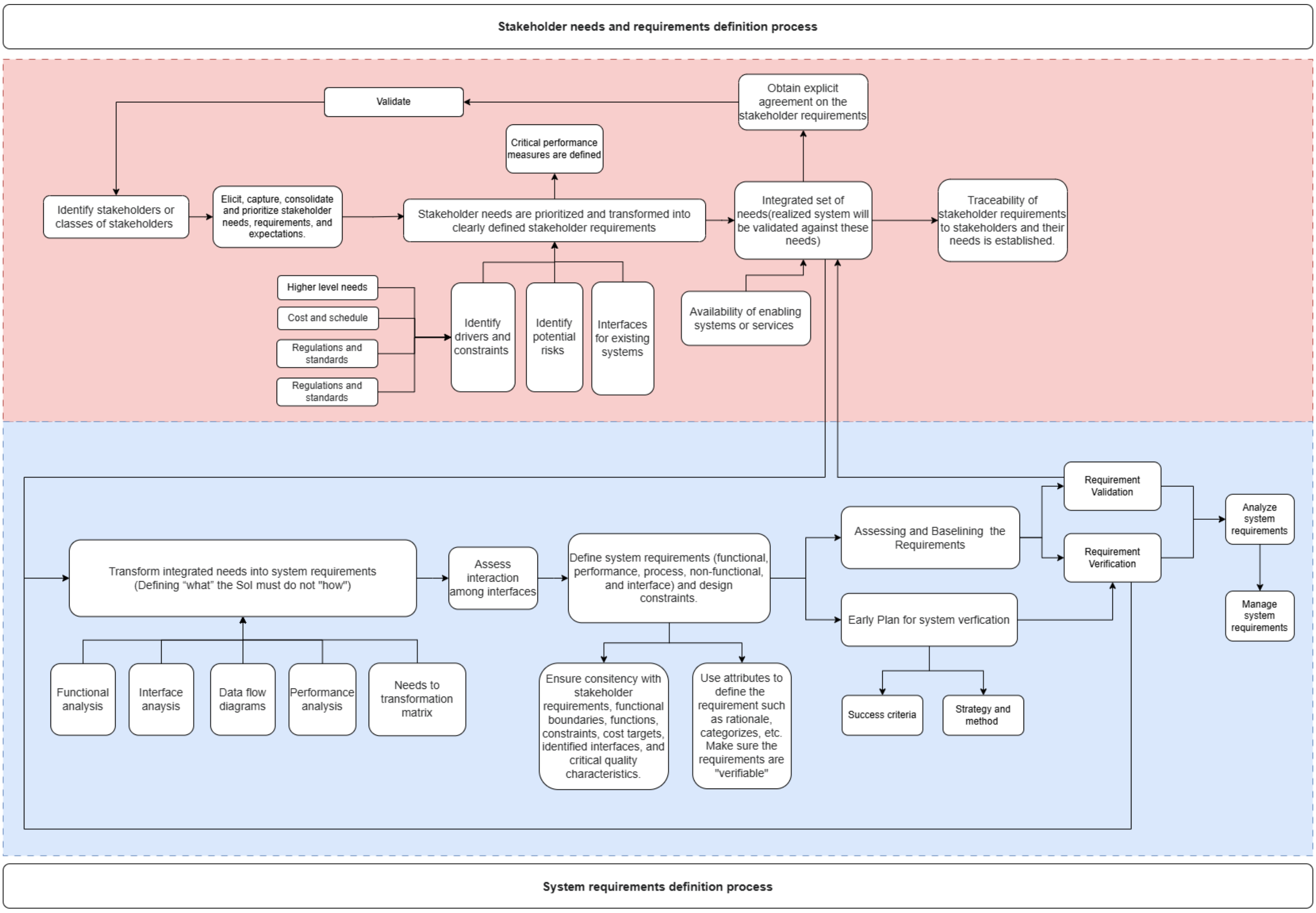

Figure 5.1: Requirement definition process, developed by author, based on INCOSE 2023, ISO/IEC/IEEE 15288:2015, and SEBoK v.2.12

However, it is important to see that effective CRS and system specifications exhibit several key attributes as described by the ProRail et al. (2013). They must be complete, addressing all disciplines and lifecycle phases. They should remain current, promptly incorporating new insights to prevent later scope adjustments or contractual disputes. Clarity is essential; specifications must be unambiguous and precisely defined. Furthermore, requirements must adhere to the SMART criteria- Specific, Measurable, Acceptable, Realistic, and Time-bound-to ensure clear objectives and feasibility. Achieving such comprehensive and high-quality specifications necessitates a collaborative approach involving multiple stakeholders and roles.

To implement these processes effectively, it requires adapting them to organizational contexts, guided by established frameworks such as ISO 15288 and the INCOSE Handbook. To understand the processes of developing stakeholders and system requirements better, the following figure (Figure 5.1) can be referred to.

5.2 Verification and Validation

V&V are two different steps defined in ISO 15288. As per ISO 15288, The verification process aims to provide objective evidence demonstrating that a system or its elements meet specified requirements and characteristics. It identifies anomalies such as: errors, defects, or faults-in information items like system requirements or architectural descriptions, implemented system components, or lifecycle processes. While The validation process ensures, through objective evidence, that the operational system fulfills stakeholder requirements and business or mission objectives in its intended environment. The primary aim of validation is to build stakeholder confidence in the system's capability to perform its intended mission or function under specific conditions. As stated in ISO 15288, "validation confirms the 'right product is built,' while verification confirms the 'product is built right.'"

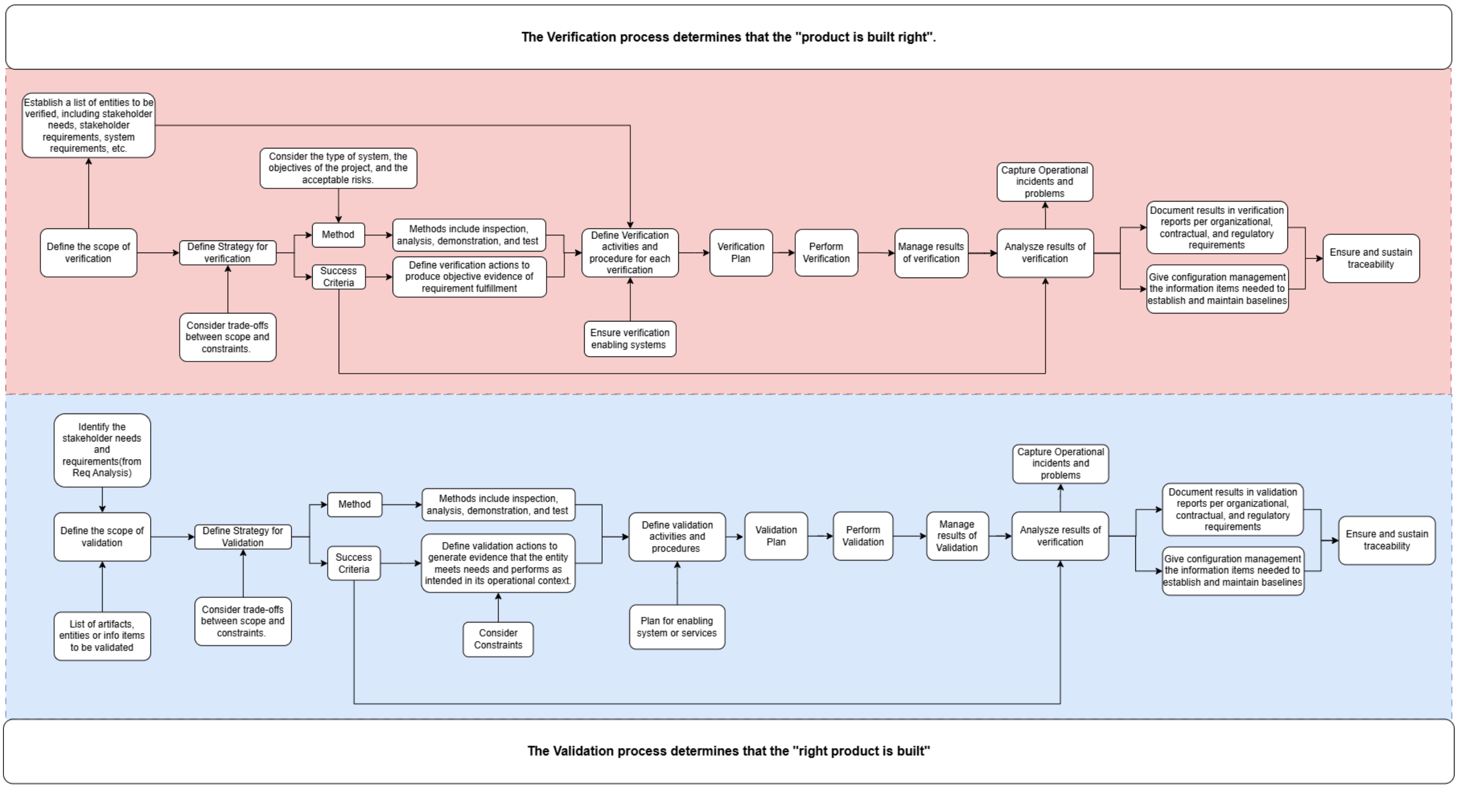

Figure 5.2: Verification and Validation Process developed by author, based on INCOSE 2023, ISO/IEC/IEEE 15288:2015, and SEBoK v.2.12

According to ProRail et al. (2013), V&V occurs at different stages in a construction project, when seen from the client's point of view. V&V in different phases is explained below:

- Exploration Phase: Stakeholder needs are captured as customer requirements and translated into system requirements. Validation ensures the translation aligns with stakeholder intent, while designs developed from these requirements are verified for consistency. Conflicts are resolved through feedback, and outcomes shape future development.
- Concept Phase: A V&V management plan is established by the client to define strategies, criteria, and responsibilities. This plan ensures alignment between client and contractors, with updated customer requirements validated for traceable approval before progressing further.
- Specification and Pre-Contract Phase: V&V are conducted iteratively across all levels of detail. Early application, even before contracting, ensures design choices and requirements meet technical

and stakeholder expectations. Quantitative metrics guide verification; expert judgment supports validation.

- Development Phase: Contractors refine and apply the V&V strategy in their own plans, aligning with client expectations. Verification is performed against derived requirements; validation is done with stakeholders to confirm the design's adequacy before construction, minimizing risk and avoiding rework.

5.3 Other related processes

1) Traceability and Information management

Traceability is a fundamental outcome shared across all technical processes defined in ISO 15288! At the core of ensuring traceability lies effective information management, which facilitates the structured handling of information throughout the system life cycle.

According to ISO 15288, the Information Management process involves the generation, verification, transformation, retention, dissemination, and eventual disposal of information to relevant stakeholders. It ensures that all information-be it technical, organizational, contractual, or user-based-is complete, verifiable, consistent, modifiable, traceable, and clearly presented. International Council on Systems Engineering (INCOSE) (2023) further emphasizes the close alignment of information management with configuration management. This coordination is essential to control data integrity, manage initial releases, and implement changes throughout the system life cycle-from concept to disposal. As information exists in multiple formats and holds varying significance within an organization, interoperability becomes a key requirement.

In large-scale projects, information is often dispersed across teams, locations, and life cycle phases. The Guideline by ProRail et al. (2013) highlights the need for explicit and traceable working practices, particularly because such transparency is not always intuitive. Working explicitly means clearly documenting decisions, including the rationale behind them, at the moment they are made. Doing so enhances traceability and ensures shared understanding. Projects must therefore create an environment that supports this approach by specifying in the project plan what information should be recorded and exchanged. Overall, the integration of traceability with information management enhances decision accountability and lifecycle continuity, while also requiring a cultural and procedural shift toward more deliberate and transparent documentation practices.

2) Configuration Management and Change Control

Configuration management is a fundamental process in SE that ensures a clear and consistent understanding of the system's structure throughout its life cycle. In civil engineering projects, which often involve modifications to existing infrastructure, defining and maintaining a system's configuration is critical. Ideally, this configuration is documented from the outset in a Configuration Management Database (ProRail et al., 2013). If such a database is not yet available, it should be established as early as possible, even for smaller maintenance projects so that the system's status is accurately recorded and traceable at all times. The primary aim of configuration management is to ensure that all project participants operate from a single source of truth. This uniformity supports consistency between subproducts and enables controlled implementation of changes, reducing the risk of errors. Central to this process is the concept of a baseline i.e., a formally agreed version of the system at a specific moment in time (SEBoK, 2024).

Change control is closely integrated with configuration management and becomes essential once requirements are baselined. As defined in SEBoK (2024), baseline management enables projects to assess and control changes to needs and requirements, including cost and schedule impacts. Change drivers may include evolving stakeholder expectations, budget shifts, risk emergence, or updates in the operational environment. Because of the iterative nature of SE, such changes are especially common in early development stages. A well-maintained configuration also simplifies change handling: proposals can be evaluated through structured impact analyses using reliable data, making the overall process more transparent and efficient (ProRail et al., 2013).

6

Case Study- 2GW Introduction

The TenneT 2GW Program introduces a transformative offshore grid connection standard that is aimed at expediting the European energy transition. By employing a high degree of technological and procedural standardisation, the program enables faster deployment of offshore wind infrastructure while reducing costs and environmental impact. The 2GW standard refers to a modular, scalable HVDC platform that significantly increases transmission capacity. Each system comprises an offshore converter station, a new 525 kV bipolar HVDC cable system, and an onshore converter station that is designed to interconnect with other systems in a future European meshed HVDC grid. This design not only simplifies replication and planning but also supports long-term integration across national borders, ensuring energy security and system flexibility.

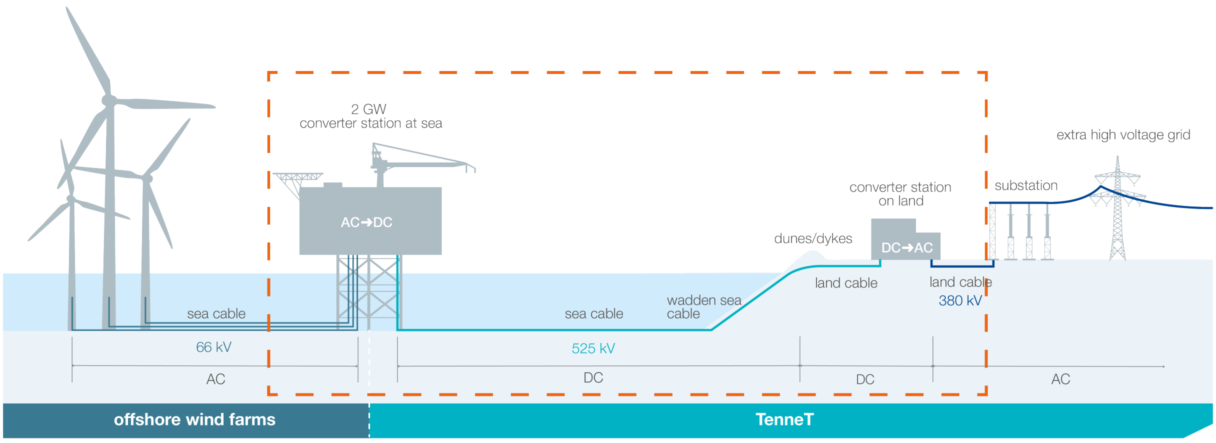

Figure 6.1: 2GW Program - Projects scope

TenneT will deliver 14 offshore grid connections, each with a transmission capacity of 2 GW, in the German and Dutch North Sea by 2031, collectively contributing to 28 GW of capacity. This represents roughly 30% of the EU's 2030 offshore wind energy target.

- Netherlands (8 systems): IJmuiden Ver (Alpha, Beta, Gamma), Nederwiek (1, 2, 3), Doordewind

(1, 2)

- Germany (6 systems): BalWin (3, 4) and LanWin (1, 2, 4, 5)

The 2GW Program's partnering and procurement approach is as innovative as its technical model. Rather than managing each grid connection system in isolation, TenneT has implemented large-scale, bundled tenders for HVDC platforms and cable systems. This ensures better planning reliability, enhances supplier capacity, and secures long-term market commitment. Standardized FIDIC-based contracts are used to align technical, administrative, and legal processes, streamlining project implementation and reducing delays. These frameworks foster collaboration between stakeholders, reinforce mutual responsibility, and unlock economies of scale, making the overall grid expansion safer, faster, and more cost-efficient.

The major strategic goals of the 2 GW can be broadly explained on the basis of the documentation in the form of 2GW Program Charter, standardization policy, and 2GW Goals and ambitions documentation. At the heart of this 2GW initiative lies a commitment to superior safety and corporate social responsibility which ensures that harm to people, assets, and the environment is minimized well beyond European benchmarks. This is made possible through a well defined safety-by-design philosophy and harmonized CSR frameworks that guide every phase of project execution. Further, driven by a culture of continuous learning, the program aims to integrate lessons from past projects in Germany and the Netherlands, as well as insights emerging from ongoing 2GW initiatives. This knowledge transfer not only enhances project outcomes but also strengthens resilience and innovation over time. Through on-time delivery, TenneT ensures that all infrastructure is completed in line with commitments made to national governments, safeguarding regulatory trust and public confidence.

A major pillar of the program is lifecycle optimization. It means designing and operating assets to achieve the lowest possible Total expenditure (TOTEX) over their entire lifespan, from commissioning to decommissioning. To enable this, standardized technical design is applied consistently across projects, within the limits of national legislation, ensuring coherence, compatibility, and efficiency. This is paired with a unified execution model called "One TenneT" that fosters consistent processes, transparency, and ongoing engagement with internal and external stakeholders. The 2GW Program is also closely aligned with broader strategic and governmental objectives. By reducing lead times, streamlining procurement, and facilitating cross-border interconnection, TenneT supports the realization of long-term European energy integration goals. Ultimately, the program aims to significantly lower the Levelised Cost of Energy(LCoE) for offshore wind, making renewable energy not just greener, but also more economically viable for all.

6.1 Goals realization Philosophy

The realization of these goals relies on a foundation built on standardisation, harmonisation, and optimisation. These are the strategic pillars that define how TenneT intends to execute its long-term offshore program efficiently and transparently. These have been described more elaborately in Appendix A.

1. Standardisation: One Unified Model for All Projects Standardisation is the key enabler for achieving speed, consistency, and scale in offshore development. Through a deliberate standardisation effort, TenneT has created a unified approach that applies to all 2GW offshore projects across the Netherlands and Germany. This ensures predictability in execution and compatibility across systems and suppliers.

2. Harmonisation: One TenneT Approach Across the Program Harmonisation ensures that all internal and external actors operate within a cohesive and collaborative framework. It brings alignment

in requirements, responsibilities, and expectations throughout the asset lifecycle.

3. Optimisation: First Time Right, with Transparent Validation and Cost Control Optimisation in the 2GW Program is about reducing waste, avoiding rework, and maximising value across the asset lifecycle. A “first time right” execution model is applied, grounded in SE, lifecycle costing, and data-driven validation.

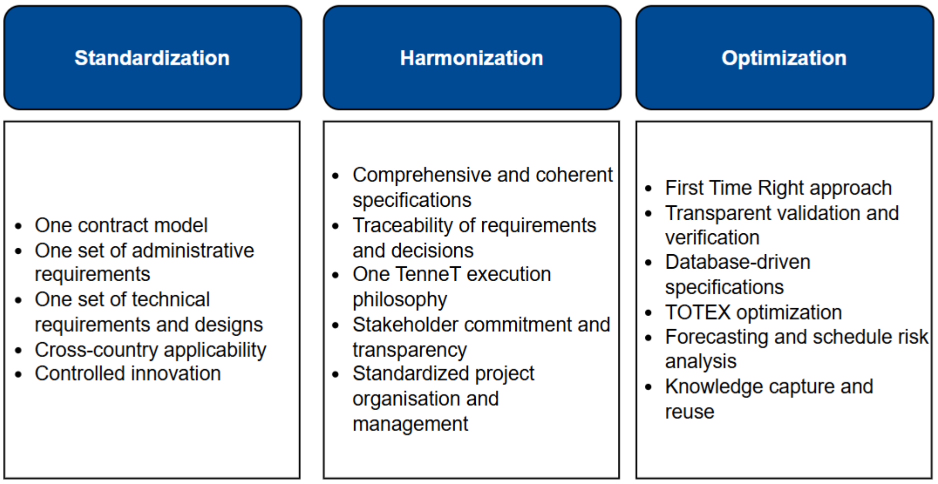

Figure 6.2: 3 Pillars of 2GW program realization philosophy

6.2 SE scope and Goals

Now to realize this successful system and aid the 2GW program Philosophy TenneT adopted the "SE Way of working". A successful system satisfies the needs of its users and stakeholders while maintaining long-term operational efficiency. (Kossiakoff et al., 2011) highlights that SE plays a crucial role in ensuring systems meet their design objectives while remaining adaptable to future changes. By anticipating and mitigating risks early in the development process, SE establishes a proactive approach to handling uncertainties. It also incorporates innovation to maintain technological competitiveness, ensuring systems are resilient and adaptable in rapidly evolving technological landscapes. Additionally, SE provides a structured approach to system validation and maintenance, ensuring that developmental problems are addressed at the earliest possible stage. This comprehensive approach results in the creation of robust, efficient, and high-performing systems. A well-executed SE approach significantly enhances project outcomes by integrating early-stage risk identification and lifecycle focus.

Within the 2GW Program, the SE scope is limited to the phases “Design the energy system” and “Build the electricity grid” of the One TenneT Process Model (OTPM). OTPM (Figure 6.3) is TenneT’s standard life cycle approach for projects. The idea is to fully develop a SE approach that will support both the 2GW Program and its partners in realising the offshore energy infrastructure that is required. Further supporting the implementation and adoption of the SE approach throughout TenneT. Finaaly the vision is to Setup and implement together with our 2GW partners a continuous improvement program to develop the capabilities of the implemented processes of ISO 15288 in our organisations to achieve the highest possible level of maturity on SE.

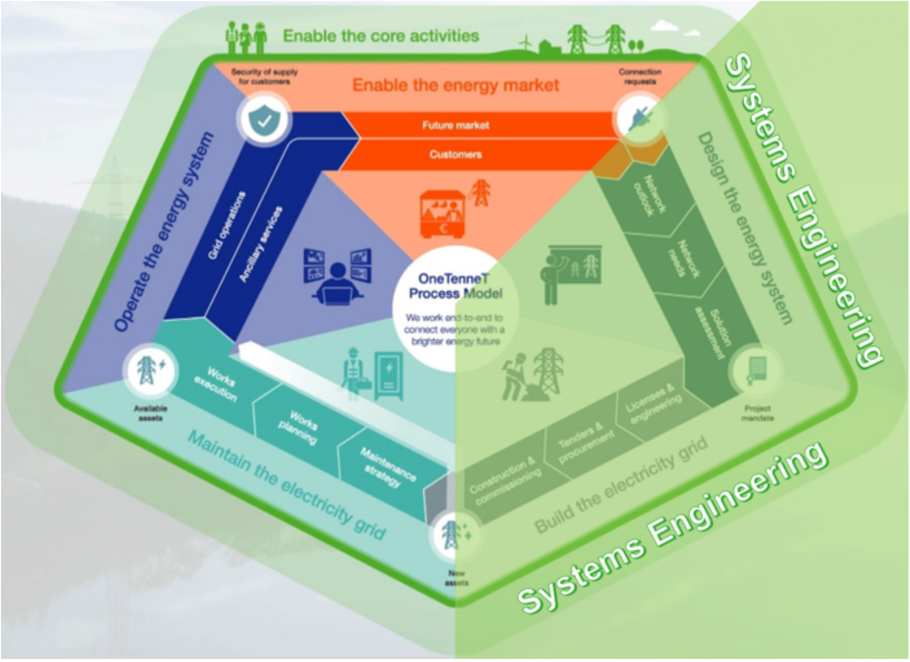

Figure 6.3: One TenneT Process Model

7

Case Study- SE Implementation

"Systems Engineering is a deterministic approach for developing successful systems that meet stakeholder needs; it is an integrated, transdisciplinary and well-structured way of thinking and working throughout the entire life cycle focusing on the wholeness of systems, which explicitly and traceably shows at any given time how a system meets the demands of the stakeholders." This definition of SE is used within TenneT and was originally presented in the Functional Directive SE version 1.0 created by the Asset Management (AMT) department.

To facilitate effective collaboration within the civil engineering sector, (ProRail et al., 2013) established a set of foundational principles, known as guiding principles, which serve as the governing framework. Over time, these principles have been refined through increased collaboration and the adoption of SE. However, There are 5 key essentials among those on which Tennet works in the 2GW Program.

Key Principles

- Systems Thinking: Viewing projects as interconnected systems, taking into account their lifecycle, integration within larger ecosystems, and involvement of multiple stakeholders.
- Life Cycle Approach (Structured Approach): The widely used V-Model explicitly relates requirements and system definition to final validation, providing a structured view of life cycle development.
- Iterative Processes: Iteration applies to both life cycle stages and processes, enabling ongoing refinement through feedback as project details evolve.
- Traceable, Explicit, and Transparent Way of Working: Ensuring clear decision-making, traceable information, and verifiable processes across the system life cycle.
- Key role for stakeholder needs: Prioritizing stakeholder needs throughout the system's life cycle rather than purely focusing on technical solutions.

It's worth emphasising that SE is an approach, a way of thinking and working, a means to an end. SE provides processes and tools that can be used to achieve a goal. Tennet uses the widely accepted V-Model(Figure 7.1), which explicitly relates requirements and system definition to final validation, providing a structured view of lifecycle development. This enables SE to systematically handle complexity and ensure reliability in large-scale engineering projects.

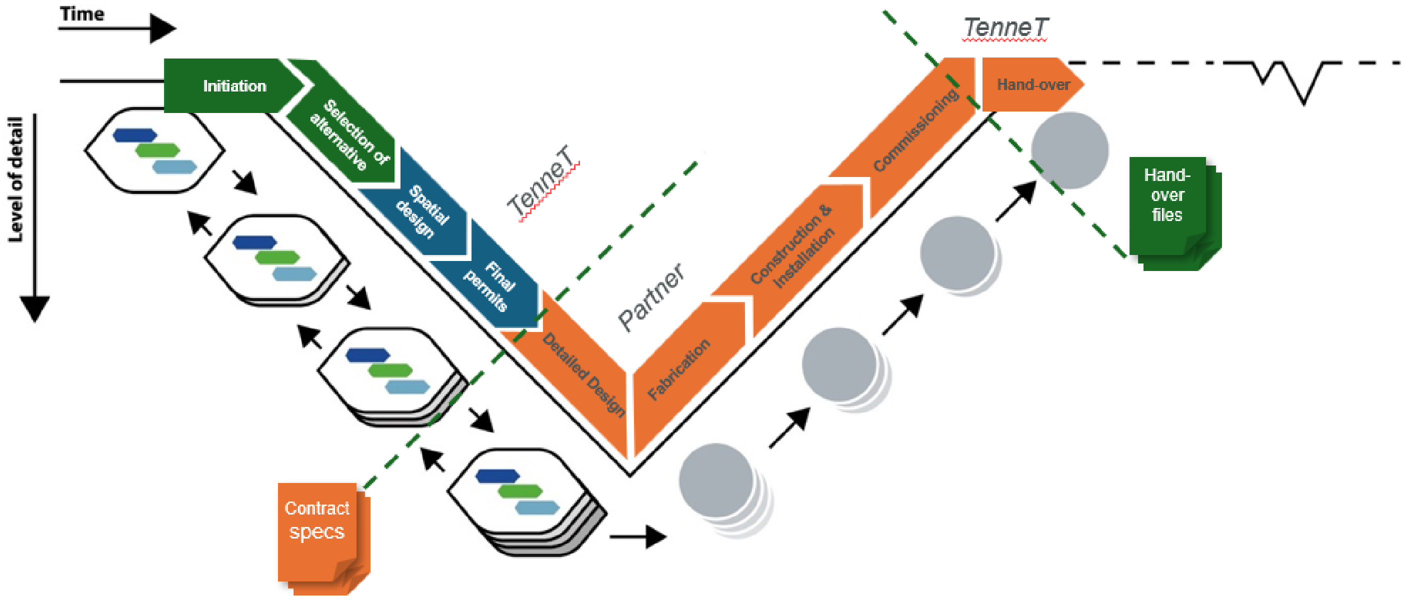

Figure 7.1: V Model - TenneT

The above key essentials of SE in Tennet are supported by the below hybrid Pyramid-V Model that represents the life cycle of a 2GW Grid Connection System (GCS), and has 8 key processes(Project assignment process, Stakeholder needs and requirements process, System architecture and analysis process, Requirement engineering process, Design process, Realisation process, V&V process, Configuration management process) covering the design the energy system and build the electricity grid phases. This model is divided into eight processes that are part of the SE approach:

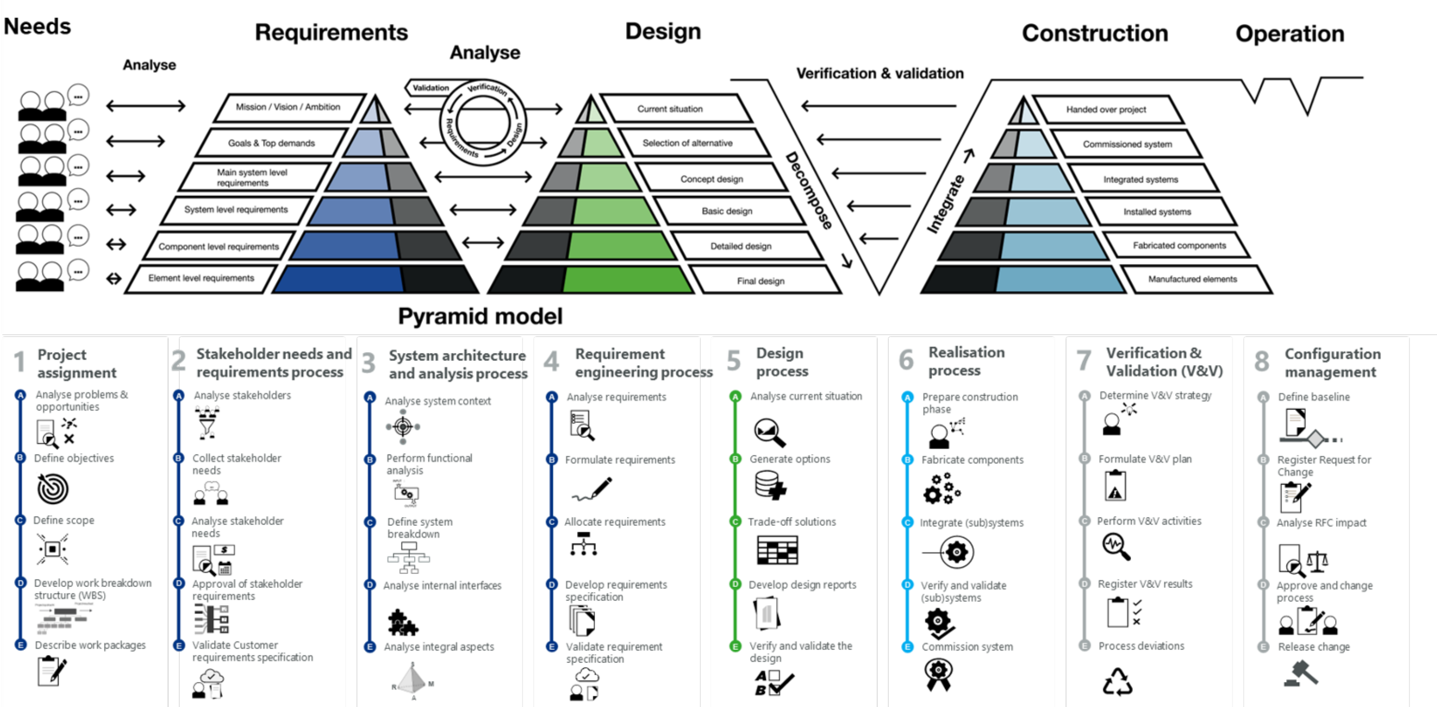

Figure 7.2: 8 Key SE Processes in TenneT

8

Interviews

Semi-structured interviews are widely used in research due to their flexibility and ability to adapt to different study contexts. As noted by Kallio et al. (2016), this method allows researchers to adjust the structure of the interview to suit the goals of the study and the nature of the topic being explored. It can be used effectively in both one-on-one and group settings. A key strength of this method is the interactive nature of the conversation between the interviewer and the participant. According to Galletta and Cross (2013), semi-structured interviews encourage a two-way exchange where interviewers can ask follow-up questions based on the responses given, while participants are encouraged to share their views in detail and in their own words. Hence, to collect meaningful and varied insights, semi-structured interviews were conducted as one of the main data collection methods. This approach offers a balance between guided questioning and open-ended discussion, making it well-suited for exploring individual experiences and perspectives. The steps followed during the interview process are shown in Figure 8.1. It allowed for the capture of diverse viewpoints, enabling a deeper understanding of personal and organizational experiences with SE. This chapter presents the process of data collection through interviews and the approach used to analyze the collected responses.

8.1 Data Collection

A semi-structured interview guide was developed in accordance with the principles outlined by Kallio et al. (2016). **(For the complete list of themes and prompts, refer to Appendix B)**. This approach provided a flexible framework of guiding questions intended to direct the conversation toward key research themes while still allowing participants the freedom to share their personal experiences and perspectives. Rather than following a strict script, the idea was to reorder questions on the fly, dive deeper where participants were most engaged, and follow up on unexpected insights. Because a small set of core themes were combined with thematic questions with open-ended prompts, interviewees could speak freely about their experiences and feelings, and new ideas could surface naturally.

The interview guide was structured around two layers of inquiry. The first layer consisted of broad themes aligned with the core research questions. Within each theme, a set of follow-up prompts was included to facilitate deeper exploration of relevant topics. Participants were not expected to respond to every question; rather, the interview process was designed to allow conversations to evolve naturally, with emphasis placed on the areas most significant to each participant. This structure ensured that interviews remained both focused and adaptable to individual perspectives. The guide was developed to follow a chronological progression, beginning with the factors that triggered the adoption of SE, moving through expectations of its implementation, and concluding with an examination of how implementation is unfolding and how it could be improved. The primary themes and sub-themes used in this timeline-based format are outlined below.

- Key Challenges and Problems in Offshore Grid Connection Projects
- Expected Benefits of SE implementation in 2GW Program
- Current Status and Challenges of SE Implementation

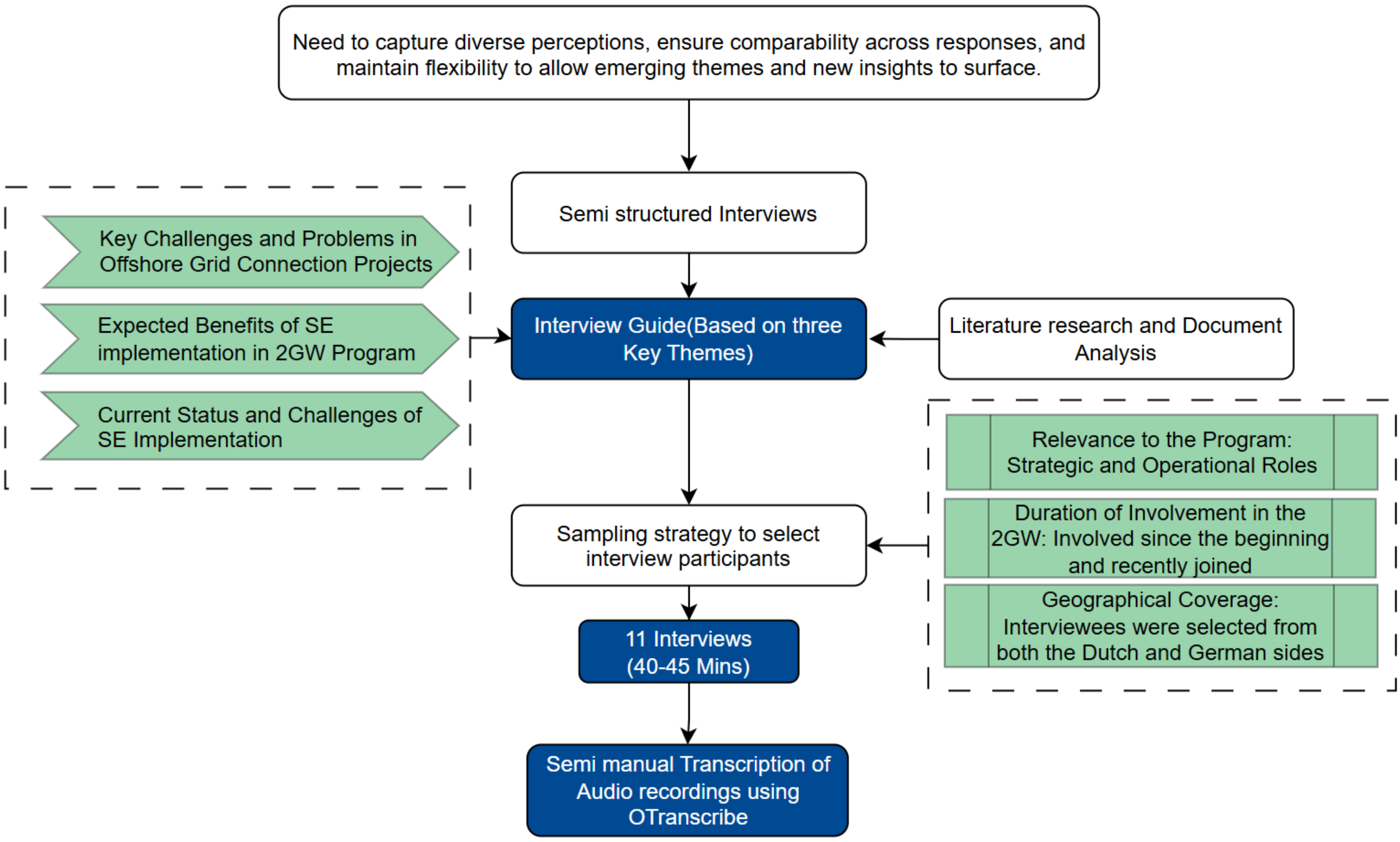

Figure 8.1: Interview Process Outline

The next step was to choose the right people for the semi-structured interviews. Sampling in qualitative research is most often conducted non-randomly and purposively, with participants deliberately selected for their relevance to the research question and their potential to provide rich, insightful data. This approach by Cunningham and Carmichael (2017) ensures that individuals are included in the study because they are particularly well-suited to illuminate the phenomena under investigation, often by virtue of their expertise, experience, or unique perspective within the field. As such, purposive sampling is a strategic and intentional process, allowing the researcher to focus on information-rich cases that are 'fit for purpose' in addressing the study's objectives.

Finally, there was a need to determine the sample size. One of the most important considerations for sample size is the point of data saturation i.e., when further interviews no longer bring new themes or insights. As noted by Bowen (2006), this point is referred to as theoretical saturation. It marks the stage at which additional data only confirms what has already been discovered, without offering new information. In this study, theoretical saturation was observed after the 9th interview, as the themes and responses began to repeat. To ensure a thorough understanding and avoid unnecessary repetition, a total of 11 interviews were conducted. This number was considered sufficient to cover the key themes while maintaining data quality. The experience and expertise of the researcher, both in qualitative interviewing and in the substantive area of inquiry, are also critical in reducing the required sample size and in achieving saturation efficiently. Additionally, the appropriateness of participant selection, ensuring that individuals possess the requisite characteristics or experiences, is fundamental to the quality and depth of the data collected.

In accordance with these principles, the present study employed a purposive sampling strategy to select interview participants (Table 8.1). The following criteria were used to select interviewees:

- Relevance to the Program: Interviewees were chosen based on their active involvement in the 2GW Program, ensuring they held either strategic or operational roles.
- Duration of Involvement: Participants included both: Individuals involved since the program's inception in 2018, who contributed to defining its foundational principles and observed its evolution. Individuals who joined during the later stages of implementation, to capture insights on current practices and adaptations.
- Geographical Coverage: Interviewees were selected from both the Dutch and German sides of the program to ensure representation across national contexts.

Each interview lasted between 35 to 45 minutes. The audio recordings were transcribed semi-manually using Microsoft Word and oTranscribe. Due to ethical and privacy considerations, the transcripts are not publicly accessible. However, anonymized versions are available in the university's internal database.This approach allowed the study to capture the experiences of those involved from the beginning, as well as those who entered during the program's implementation, in order to gain an understanding of its development and avoid data saturation.

Table 8.1: Interviewee Details for the 2GW Program Study

No.	Role in 2GW	Background	Since
1	Senior Advisor 2GW	Former program manager in the Dutch infrastructure sector with experience applying SE principles. Started the 2GW Program.	2017
2	Head of Asset Management Offshore development	Mechanical engineer by training; began career as a technical and project engineer at TenneT.	2018
3	SE Program Manager	Civil engineer and certified PMP professional with extensive experience in program management.	2023
4	Lead Project Management	Responsible for implementing SE in the 2GW program from its inception, even before the tender phase.	2018
5	SE Advisor	Worked at the Dutch Ministry of Infrastructure (Rijkswaterstaat), involved in SE adoption in public infrastructure projects.	2019
6	Lead Project Management Office	Not directly involved in SE but has supported the 2GW program for over seven years, including its initial SE strategy.	2019
7	Lead 2GW Program Office (DE)	Background in engineering management and offshore operations, with specialization in HVDC technology.	2024
8	Lead Project Management	Began in the Dutch railway sector where SE is standard; transitioned from risk manager to a role in the 2GW program.	2019

Continued on next page

Table 8.1 continued

No.	Role in 2GW	Background	Since
9	SE Manager GSC	Experience in SE and project control across Dutch construction projects.	2019
10	Sub Project Lead Project Management	Worked in SE and risk management within Dutch infrastructure and tendering processes.	2022
11	Lead Project Execution (DE)	Specialized in asset strategy and requirements management.	2020

8.2 Data Analysis

After clearly defining our research objectives and formulating our research questions, we identify a suitable qualitative research methodology aligned with our goals. Qualitative research primarily aims at theory-building rather than theory-testing, focusing on developing or elaborating concepts, relationships between concepts, and detailed descriptions of processes (Gioia et al., 2013). The expected outcomes of qualitative analysis typically involve constructing typologies, rich conceptual descriptions, categorizing individuals or organizations under specific concepts, or articulating theories that define conceptual relationships(Skjott Linneberg & Korsgaard, 2019).

Given the exploratory nature of the study, the grounded theory approach was adopted as it is beneficial for investigating phenomena that are not well understood and building new theoretical frameworks directly from empirical data. This inductive method refrains from starting with predefined hypotheses or categories; instead, it focuses on capturing and interpreting patterns and themes emerging directly from participants' responses. This is particularly valuable for understanding how SE contributes to solving the PM Issues discussed in the section 4.2 within large-scale infrastructure programs, such as TenneT's 2GW program.

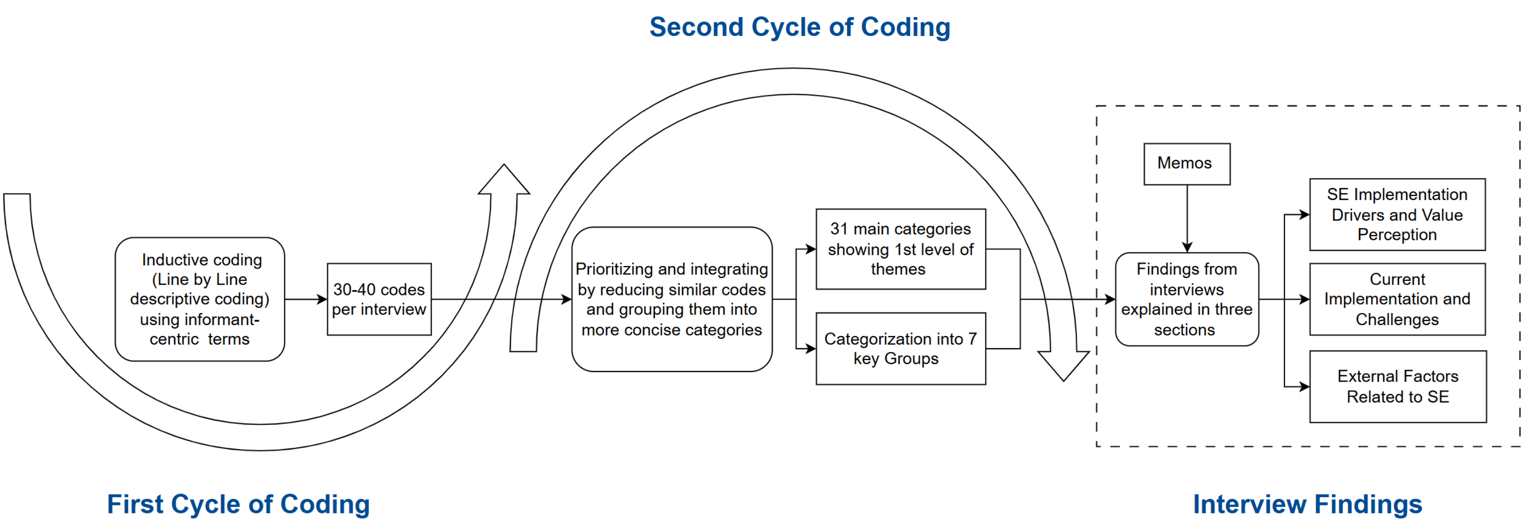

Figure 8.2: Analysis of Interview Data using ATLAS.ti

To make sense of the transcribed interview, the interviews were coded using ATLAS.Ti software (Figure 9.3). Coding involves assigning interpretive labels to emerging concepts, ideas, constructs, or themes identified within the collected data (Saldaña, 2016). Skjott Linneberg and Korsgaard (2019) suggests conceptualizing the coding process as occurring in multiple cycles. In the first cycle, an inductive approach is taken using informant-centric terms, emphasizing descriptions directly derived from participants' language. The subsequent coding cycles shift toward a researcher-centric perspective, introducing established theoretical concepts and frameworks to elevate the analysis to higher levels of abstraction and theoretical sophistication (Gioia et al., 2013). The two cycles of coding are explained in the sections below.

8.2.1 First Cycle: Inductive, Line-by-Line Coding

Inductive coding is a core tradition within qualitative research, focusing on generating codes directly from participants' language rather than relying on predetermined theoretical vocabulary. This approach helps maintain proximity to the original data, accurately reflecting participants' perspectives and experiences, while minimizing researcher bias and preconceived notions (Cunningham & Carmichael, 2017). Originating from grounded theory strategies initially developed by Glaser (1978)), inductive coding emphasizes line-by-line analysis, wherein researchers meticulously assign codes to individual lines of data. Hence, the initial codes developed were predominantly descriptive, capturing the precise meaning and context of the participants' expressions (Skjott Linneberg & Korsgaard, 2019).

So in the first cycle of coding, each interview was carefully reviewed line-by-line and they were assigned descriptive codes, usually in the form of words or short phrases. This process resulted in approximately 30-40 initial codes per interview. An example of the process is shown in Appendix C in Figure C.1. During this stage, we carefully read through transcripts, systematically identifying recurring keywords, phrases, or significant concepts expressed by participants. The analytical tool Atlas.ti facilitated this process by organizing data effectively, tracking code occurrences, and assisting in the initial grouping of related codes to reveal emerging thematic patterns. In the first cycle, approximately 30-40 codes were developed per interview.

8.2.2 Second Cycle: Developing Categories and Themes

Following the first cycle of coding, a second cycle was conducted to synthesize and refine the initial codes into higher-level categories and themes. The second cycle was more about "classifying, prioritizing, integrating, synthesizing, abstracting and conceptualizing, and theory building" (Saldaña, 2016). This iterative process transitioned the analysis from numerous detailed codes towards a manageable and conceptually robust set of themes or categories.

To maintain clarity while preserving analytical depth, codes were structured into two distinct yet complementary layers:

- 31 Main Categories: These categories form the initial thematic structure derived directly from the clustering and merging of closely related or redundant codes ***(these categories and subcodes are present in C.1)***.
- 7 Key Groups: Representing higher-order themes, these groups were strategically aligned with our main research question and sub-questions ***(the developed 7 groups are presented in C.2)***.

In the concluding phase of the analysis, four topics emerged as major discussion points consistently across the interview transcripts. These topics form the basis of the subsequent findings section, which is detailed in the following chapter. They are firmly rooted in the previously established code groups, ensuring analytical coherence and clarity. Throughout this analytical stage, detailed memos were maintained to record reflections, emerging concepts, and connections, thereby deepening interpretive insight and enhancing conceptual clarity.

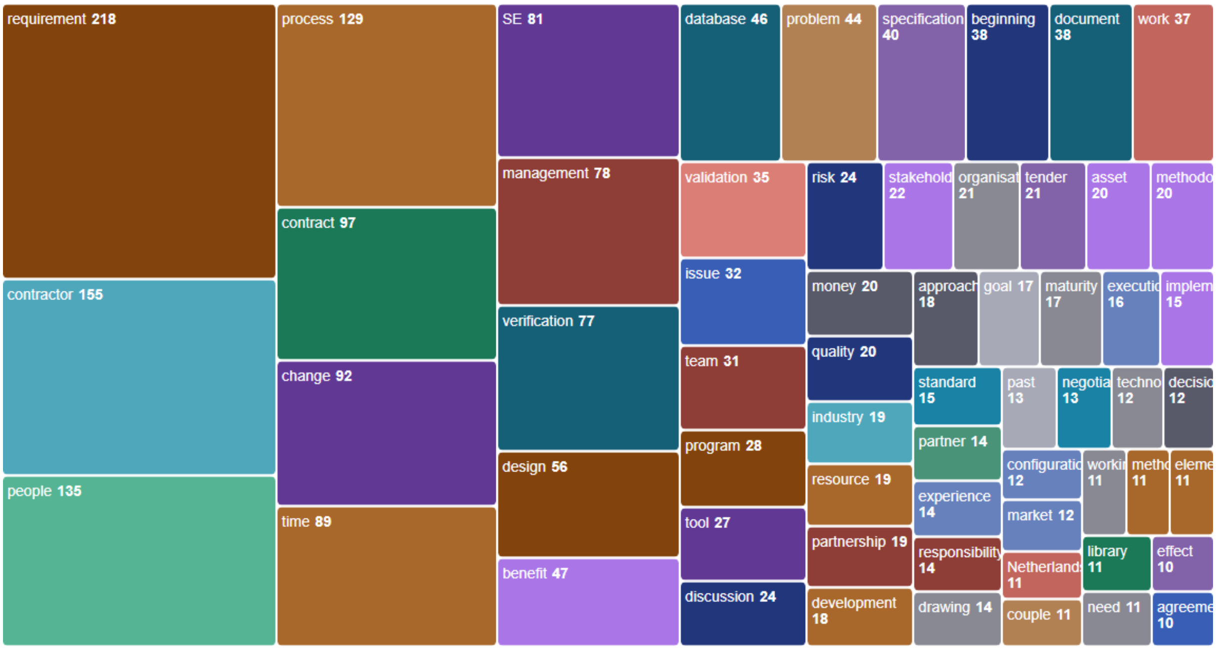

Figure 8.3: Concept Tree(Developed using ATLAS.Ti)

8.3 Data Validation

To validate our findings and ensure that the themes developed aligned with the interviewees' perspectives, respondent validation was carried out. This process took place during the analysis phase, after data collection and once the initial results were compiled (Busetto et al., 2020). The interviewees were provided with a draft of the findings in the form of a respondent validation form. This form summarizes the key points highlighted by each interviewee based on the major themes that emerged from the data analysis, namely: requirements management, V&V, explicit working through digitalization, and factors beyond SE. Participants were then asked whether the summary accurately represented their views or if they wished to clarify or elaborate on any part of their responses (Shenton, 2004). The feedback obtained through this process becomes part of the feedback cycle of data collection and analysis (Mays & Pope, 2000). Involving respondents in the validation of research instruments offers several advantages, including the opportunity to obtain more comprehensive insights and improve the quality and accuracy of the data collected. This approach is grounded in the assumption that collective expert judgments are generally more reliable than individual assessments. Respondents were also given access to their interview transcripts to verify that they accurately reflected the conversations. In summary, the responses were largely positive, with most participants agreeing that the respondent validation forms accurately captured their viewpoints. ***A few suggested minor changes have been incorporated and made available in the appendix D.***

9

Findings

This chapter presents the findings derived from the qualitative interviews conducted as part of the case study. The results emerged through a rigorous process of data analysis, including thematic coding and memo writing during and after the interviews. These findings synthesize the perspectives of 2GW participants regarding the implementation and perceived benefits of SE, as well as areas identified for improvement. Each section is structured in a narrative format to trace the developmental phases of SE as experienced by the participants.

9.1 SE Implementation Drivers and Value Perception

This section reports the key insights from the analysis of factors influencing the adoption of SE principles, particularly from the perspective of TenneT as an offshore client. Three central themes emerged from the data: requirements management, V&V, and explicit working enabled by digitalization. Each theme is examined in terms of the specific challenges encountered, along with the anticipated improvements and benefits as SE practices are progressively adopted by stakeholders.

9.1.1 Requirement Management

In earlier offshore grid connection projects, such as the 700 MW and 900 MW projects, requirements management was highly unstructured and fragmented. Requirements were written in prose, stored in spreadsheets, and finalized as PDFs. These often lack clarity, traceability, and alignment with lifecycle needs. For example, the 700 MW project generated over 2,000 documents despite its limited scope, with no assurance that the requirements were SMART, functional, or consistently interpreted. Responsibility for these documents was widely dispersed, with approximately 70 different owners contributing to the requirement sets. This diluted accountability and made it difficult to verify whether all requirements were fulfilled. Moreover, the requirements were not based on a lifecycle approach and lacked input from essential stakeholders such as grid design, licensing, and maintenance teams. This often led to misalignments during execution, frequent design changes, and escalating project risks, as late-stage adjustments frequently caused delays and claims from contractors.

> *"...But especially with requirements, I don't know if you've seen the requirements how we had them in the past. Those were hundreds of pages of text. Just Prosa text. I asked my colleagues in the project teams, how do you know that all these requirements are fulfilled?"*

“We’re finishing the detailed design, so how should I change my design while I’m finishing it? If you want to have a different type of transformer or an additional one, it’s affecting so much. It’s always affecting money, your timeline. So you don’t want it...”

Efforts to improve requirement quality began as early as 2013, but the 2GW Program significantly accelerated this transition. The need for a structured and traceable approach to requirements management was a key driver for the adoption of SE. The idea was that SE will help in early stakeholder involvement and support the structured translation of customer needs into precise, lifecycle-based requirements. This further enables the identification of explicit trade-offs and ensures that requirements are functional and SMART. The adoption of life cycle concept in design phases leads to a noticeable reduction in late-stage design changes. Such changes often impact system interfaces, consume engineering resources, create uncertainty, and result in project delays. Given the tight schedules in these programs, even minor delays can become critical. Frequent claims and disputes emerged in previous projects when project demands deviated from the original specifications. SE could help mitigate these issues by securing high-level functional requirements early in the process and managing interfaces more effectively. It also ensures a smooth project handover to internal stakeholders, such as GFO and operations. Past projects had faced significant issues during handover due to missing validations and lack of stakeholder engagement throughout the development phase. To avoid this, SE emphasizes early involvement of stakeholders and translation of their needs into requirements. These are then verified and validated during the design and execution stages.

“You want to prevent these issues, and that’s why in the beginning we involve the stakeholders... so then at the end you can say OK, check, check, check ...we can show you.”

9.1.2 Verification and Validation

With the absence of a systematic V&V process it was difficult and time consuming to ensure that contractor outputs fulfilled all specified requirements. Contractors, including major industry players such as Siemens, Hitachi, and General Electric, were initially unfamiliar with the expectations surrounding V&V process and in line with the process they were required to verify their work against defined requirements and demonstrate compliance. This process was seen as a fundamental principle of quality management within Tennet that needed to be structured. There was no structured confirmation that compliance whether contractual, regulatory, or design-related had been achieved. As one interviewee noted:

"There are all kinds of issues. And maybe some of them could have been prevented if... every time [we] have the verification loop and when you start construction, that you do the check... that helps to detect issues in a very early stage and prevent that you will have to fix them offshore years after commissioning...How do you know if the contract has delivered what we asked and paid for if you don’t have a verification?"

In the earlier projects, TenneT experienced significant rework due to an unclear division of responsibilities between the client and contractors. Traditional approaches involved redundant review cycles: contractors produced drawings, checked and approved them internally, and then TenneT repeated the entire review process. SE disrupts this cycle by fostering trust in the contractor’s verification process. When the contractor’s verification is thorough and reliable, there is no longer a need for TenneT to recheck each drawing. Under SE, TenneT, as the client, shifted the responsibilities for design V&V to the contractors. This structural change allowed TenneT engineers to concentrate on essential overviewing rather than reviewing every drawing in detail. The intent was to limit their scope, optimize the use of internal resources, and accelerate project timelines.

> *"...They have 10 engineers. Why do you have 10 engineers? You can do this with one. Now the contractor is responsible...The contractor is responsible for making the design. Contractor is responsible to check whether the design fits the requirements."*

The V&V process was introduced to create mutual benefits. Contractors gained assurance through SE documentation that their designs met client expectations, while TenneT could ensure compliance with specified requirements, with non compliance resulting in withheld payments. V&V helps identify design flaws early during the concept or basic design phases before they escalate into costly offshore fixes during post commissioning. The process serves as both as a compliance tool and as a resource efficiency mechanism.

9.1.3 Explicit working by Digitalization

As discussed in the above sections, one of the foundational challenges in past projects from the client's perspective(TenneT) was the lack of logically structured and traceable requirements. Requirements were often scattered across multiple PDF documents, lacking consistency and clarity. It was unclear where a requirement originated, who had made decisions regarding it, and what rationale supported its inclusion. The document-based approach made it difficult to track dependencies and manage interfaces between specifications. For example, lets say when a specialist modified content on page 56 of Document #18123 that interfaced with Document #2, page 26, there was no systematic method to notify others or manage the resulting consequences. In the absence of structured digitalization, teams had to recreate content for each new project, with no clear way to communicate to contractors which elements remained unchanged. This led to inefficiencies and unoptimized knowledge transfer.

> *"...requirement originate and the person A say this and then we decided on this and what is the reason behind the specification?..."*

> *"Did you implement the lessons learned and what is different in platform 2 than in platform 3?"*

Now as the 2GW projects were managed at the program level, incorporating principles such as "partnership agreement," "standardization," and "design once, build many," the expected number of interfaces between projects and portfolios increased significantly. To address this complexity, TenneT implemented a centralized, structured database of requirements. The system allows clear traceability from high-level CRS to system requirements (SRS), enabling logical follow-up and effective change tracking. Using platforms like Relatics, all requirements are now digital, structured, and easily navigable across multiple systems and contracts. The idea of adopting a digital way of working was to eliminate duplicated requirements across documents, reduced redundancy, and enabled the reuse of generic requirements. In a document-based setup it was difficult to identify changes between projects specially with interconnected systems and specifications, assessing the interface implications of a single change was difficult. The consequences of unmanaged changes were significant: a single requirement modification could lead to interface rework, drain engineering capacity, and trigger project delays. Moreover, changes introduced during later project phases often incurred substantial additional costs especially when implemented offshore or retroactively across multiple platforms. Traceability through the requirement database was required to monitor what changed, when, and why across a timeline extending over ten years. This long-term visibility was a key objective from the outset of the 2GW Program.

"If this requirement is changed, that has an effect on certain functions, that has an effect on certain systems, and that's all... explicit and traceable." "We have much better traceability on what has changed and what is changing in the specifications..."

Digitalization also improved cooperation and integrality across departments. All stakeholders including grid design, asset management, and licensing now work within the same environment and tool (Relatics). By enforcing a single standardized system across all disciplines, collaboration became more effective, regardless of organizational boundaries. This shift allowed TenneT to transition from project-specific repositories to a program-level requirements library. As a result, deviations and baselines could be tracked with each contractor, supporting consistent management of partnerships.

9.2 Current Implementation and Challenges

With the 2GW Program now in progress, this section examines the alignment between initial expectations outlined in the previous chapter and the realities of SE implementation. It highlights both the advancements achieved and the challenges encountered during execution. The deployment of SE within the case study has followed a phased and evolutionary trajectory. The initial phase prioritized foundational elements, particularly requirements engineering, rather than a comprehensive SE rollout. Subsequently, the focus shifted to contract preparation, during which V&V processes were formally defined and embedded within contractual documentation. As projects transitioned from tendering to execution, the scope of SE application expanded to encompass contract management and the formalization of procedures for handling verification reports throughout the project life cycle. Notably, these processes were developed in parallel with ongoing contract execution, rather than being fully established beforehand.

This reactive approach was largely driven by time constraints and the continuous addition of new projects to the program. As one of the interviewee noted: "It was not like this tender process was well described and developed before the tender started, it was more along the way we started to implement new things." Despite the incremental and reactive nature of implementation, this phased strategy enabled iterative learning, system refinement, and gradual stakeholder buy in: both internally and externally. The following subsections explore four key themes that emerged during this stage: Requirements Engineering, V&V, Configuration Management and Explicit working by digitalization.

9.2.1 Requirement Management

The initial phase of the initiative focused on enhancing the quality and clarity of requirements by introducing structured methodologies to facilitate digitalization. In prior projects, requirements were often excessively detailed, solution-driven, and lacked adherence to the SMART criteria (Specific, Measurable, Achievable, Relevant, Time-bound). This resulted in ambiguity, limited traceability, and challenges in downstream project phases. The integration of SE-based requirement engineering yielded significant improvements. One of the primary benefits was the standardization of requirement structures across projects, enabling a "design once, build many" paradigm that substantially increased efficiency. The structured requirements also contributed to clearer, more enforceable contractual agreements. Ambiguous language such as "a nice visible colour" was replaced with precise, objective terminology (e.g., "the platform shall be yellow"), reducing interpretive discrepancies. Adopting a lifecycle-oriented approach to requirements development minimized late-stage design changes and associated cost escalations. Early identification of compliance issues further reduced the risk of claims and contractual disputes.

"Contracts are less vague... the specifics of the requirements enhanced significantly. If you compare it to the older contracts, the 700 and 900 MW, they are now far clearer."

"A couple of years ago, we always had endless discussions... 'Now we're going to build something that doesn't fit within the licensing requirement.' I didn't hear that in the last two years."

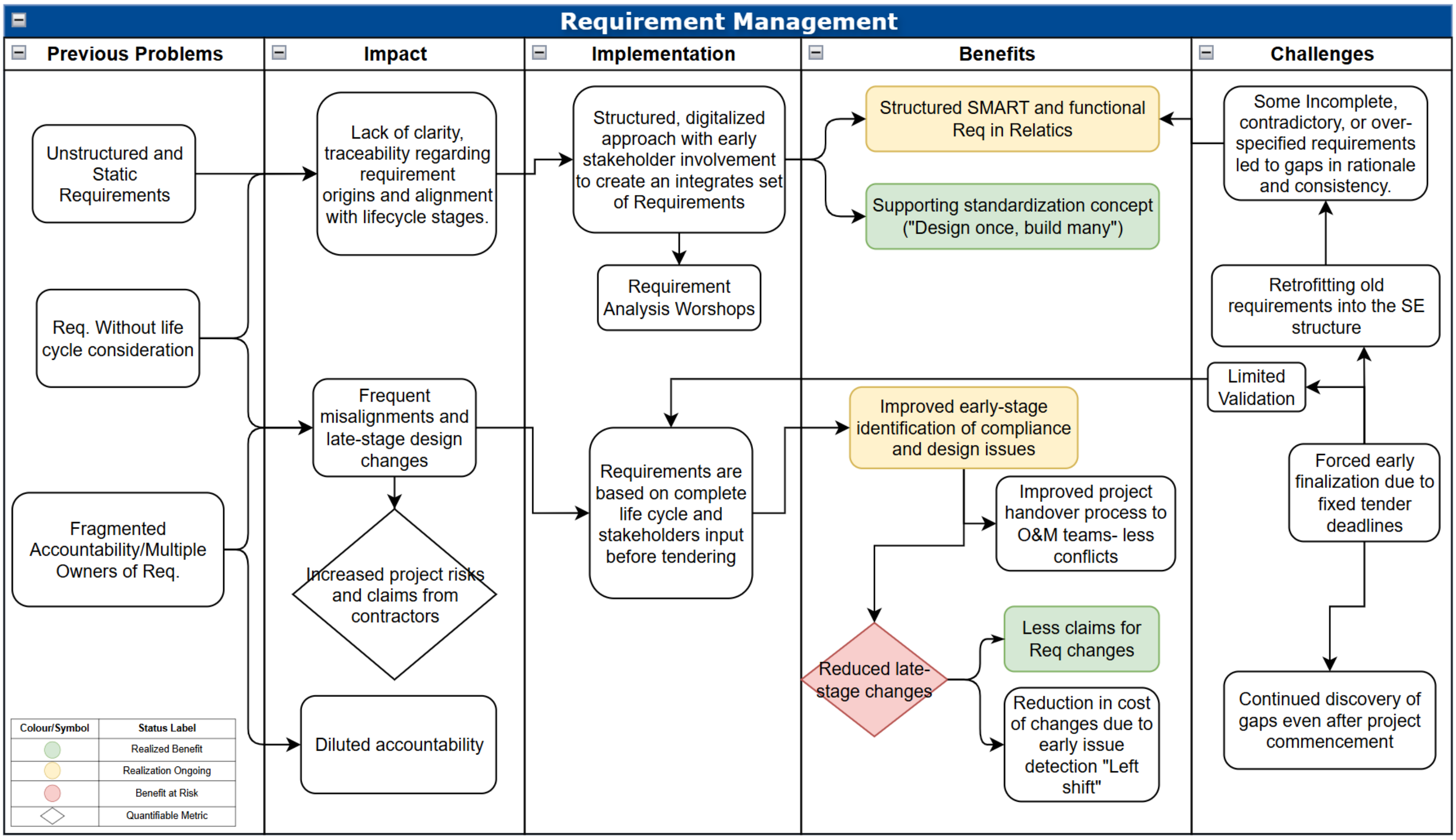

Figure 9.1: Analysis of Theme 1 - Requirement Management in the case study

However, the implementation process was not without challenges. A critical limitation was the necessity to meet rigid tender deadlines, which often compelled the premature finalization of requirements. As a result, requirements development overlapped with the tendering phase rather than being completed beforehand. This overlap persisted even after contract award, with significant gaps in requirements continuing to surface during project execution. The compressed timeline also hindered comprehensive validation efforts, leading to unforeseen issues during implementation.

"We needed to start with structuring functional requirements: what do we want? What do we do? So we started from the beginning and still used the old input. But rewriting these requirements as SE does... that took us maybe two years." "We were definitely not finished yet, but there was so much time pressure on these projects that they just had to start the tenders."

9.2.2 Verification and Validation

Within earlier projects, the fulfillment of requirements by contractors was not systematically verified. While validation practices were there ensuring that the end product meets the needs of stakeholders were already in place to some extent, they lacked formal structure. With SE, a clear and structured verification process was introduced for the first time, creating a major difference in how projects were managed. The V&V process stated that contractors are explicitly responsible for proving that each requirement is fulfilled. Verification strategies were defined, moments identified, and for each of the portfolio's employers, each employer requirement (ER) over 12,500 of them, were matched to a specific verification method and point in the project lifecycle. The goal was to reduce the client's involvement in day-to-day design reviews and increase the accountability of the market parties. This transition was initially challenging, as many perceived the V&V processes as adding extra work. In reality, however, the effort required was often less than traditional approaches.

> *"You are just putting a check... earlier they(client project team) used to check complete drawings and each detail. Now they just have to check whether the verification reports are correct and comply with the requirements."*

> *"We now have an integral verification plan... our contractor was now able to, for each and every one of them (ERs) appoint the verification method, a verification moment, basically a verification strategy for the first time after we started our contract two years ago!"*

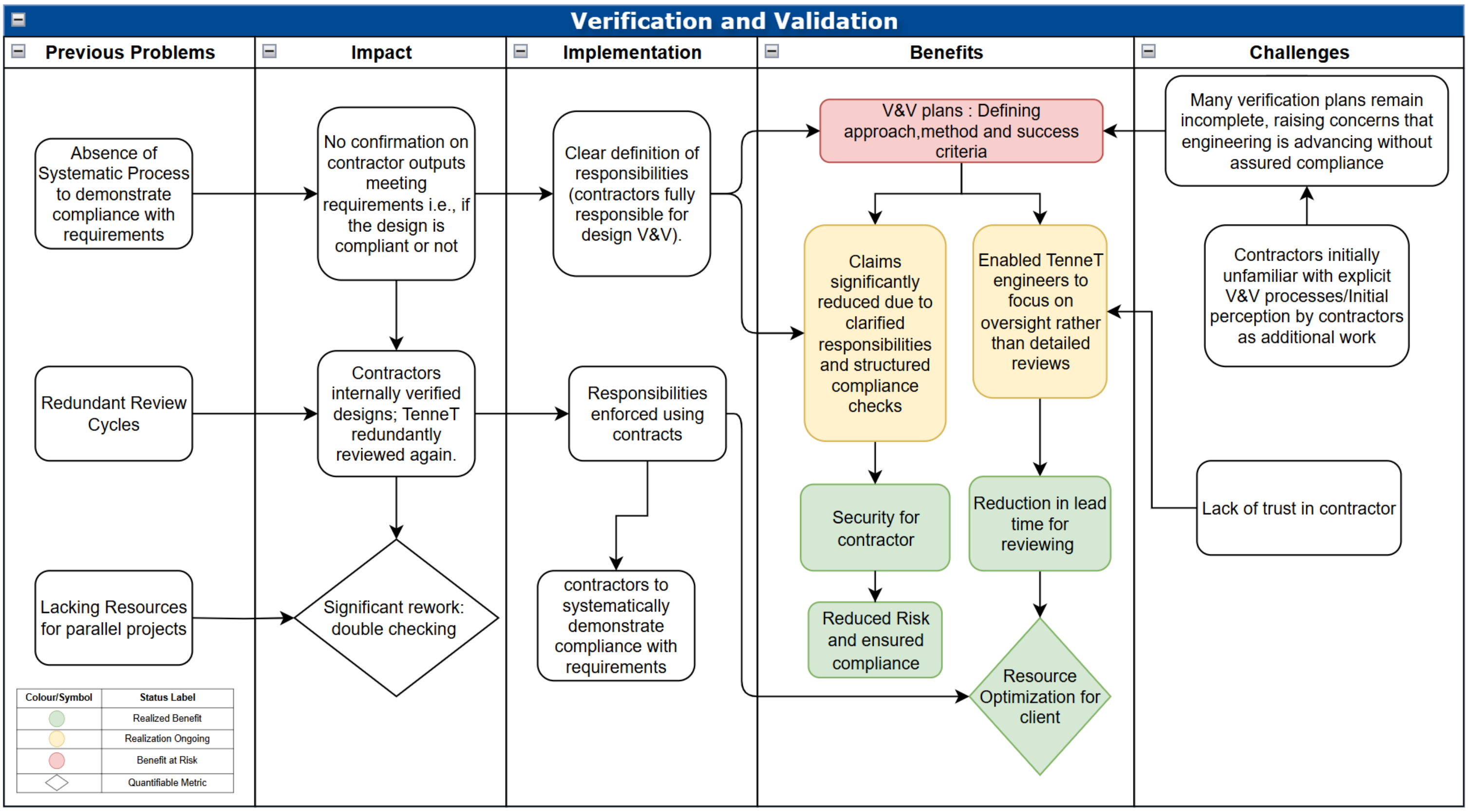

Figure 9.2: Analysis of Theme 2 - V&V in the case study

This eventually led to discussions between contractors and TenneT more black and white. If something is defined in the contract, it must be fulfilled. If it is not, it is not enforceable. This applied equally to technical and process requirements and provided transparency and fairness in contract enforcement. One of the clearest outcomes of this structured approach has been a significant reduction in claims. Under the previous system, unclear responsibilities and vague specifications often led to disputes. As a result, claims have decreased both in number and in severity.

"If there's no requirement, you don't have to do it. And that's the same for administrative requirements or process requirements...We hardly have any claims anymore. We used to have many claims, now we still have a few, but not even close to the number we had five years ago."

9.2.3 Configuration management

Configuration management previously existed at TenneT, but the scale of the 2GW program required a more transparent approach. Initially, configuration changes were managed manually via document updates, a process considered inefficient. As requirements are now structured and made SMART and digitalized, any proposed change is easier to locate, understand, and evaluate. Workshops for requirement analysis often reveal ambiguities or fulfillment issues, and while these sometimes arise post-contract, they are at least now documented and traceable, enabling structured decision-making and post-signature dialogue. To manage configuration complexity across the program, the use of centralized libraries has been introduced. Information can now be pushed from one library to another, allowing consistent updates across multiple projects.

"With SE all the changes are more visible now... So it helps us to make it more transparent who is responsible and where we are not clear."

However, governance of changes within a multi-project context posed challenges. In a single-project environment, a requirement change simply translates into a contractual amendment. However, within a program like 2GW , comprising multiple parallel projects that share standardized platforms, one change can have cascading effects. It may affect one project, several, or an entire portfolio. It may be applicable to one contractor or to many. The complexity makes it difficult to define who holds authority over such changes: asset management, the project team, or program governance. Given these difficulties, a restrictive policy was adopted i.e., most change requests are rejected unless they impact safety, maintainability, or operational continuity. Stakeholders are advised to raise concerns early in the process, as late-stage changes are heavily discouraged.

"A change in requirement means a change in contract... Then who approves the change?"

9.2.4 Explicit Working by Digitalization

The transition to explicit and traceable working practices within the 2GW program was significantly supported by the adoption of Relatics, a centralized information management tool. A key milestone in enhancing traceability and alignment across projects was the move from isolated, project-specific databases to a unified, program-level library. This strategic shift enabled TenneT to manage shared requirements and contract deviations consistently across all 2GW initiatives. By centralizing information, the team gained the ability to monitor deviations negotiated with individual partners while maintaining a clear and consistent contractual baseline. This shared system not only improved cross-departmental collaboration but also reinforced the overarching goals of the "program". By committing all disciplines to operate within the same toolset, TenneT ensured consistency and simplified collaboration, regardless of organizational function.

"You see it throughout Relatics. You can trace it back from the SRS to the CRS... check, track it for all of them. I think that's really a big win also for our contractor."

"We are much better able to scale and to make use of the functionalities of the database... that provides really a lot of tools to manage this complexity and keep in control of this very complex program."

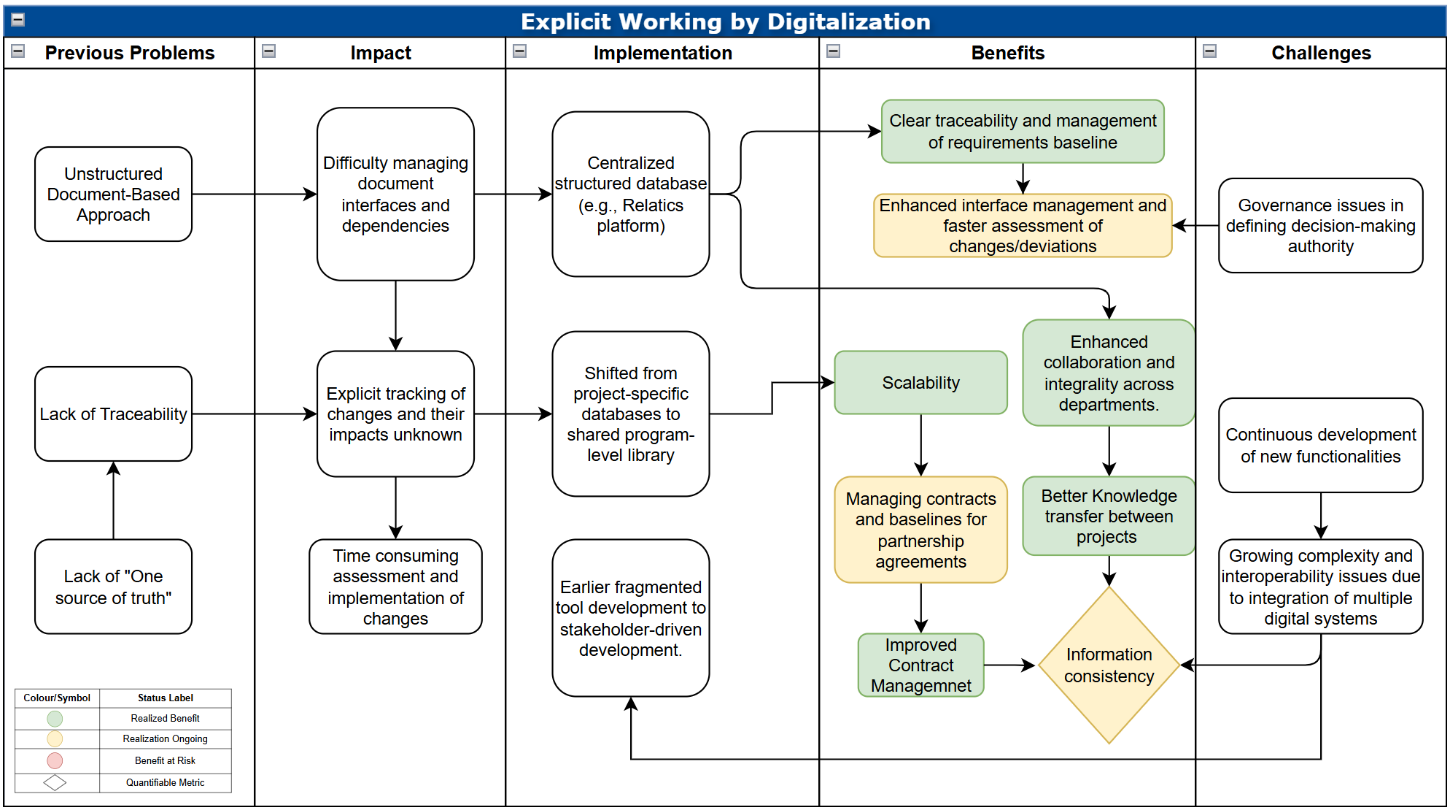

Figure 9.3: Analysis of Theme 3- Explicit Working by Digitalization in the case study

However as Relatics improved transparency and traceability of requirements, it also highlighted deficiencies, revealing many requirements as incomplete or incorrect, requiring ongoing refinement. Additionally, as the system has evolved, its complexity has grown. Attempts to link Relatics with other digital tools and platforms have introduced interoperability issues, sometimes reaching a level where the system's overall transparency is compromised due to its own complexity.

9.3 External Factors related to SE

There are many touchpoints and overlaps between SE and other disciplines. SE is closely integrated with project teams, program teams, and various other functions, making it essential to view its benefits in a collaborative context to understand that SE does not operate in isolation. This interconnected nature is especially important in offshore grid projects, where interdependencies are high. Therefore, understanding the impact of external factors is crucial, as they have influenced the outcomes in both supportive and challenging ways. These factors are discussed below:

- **Cost Drivers Beyond SE**

  Rising contract costs in the 2GW program were shaped by multiple influences. One notable factor was the use of highly detailed or "gold-plated" specifications, which often went beyond functional requirements. These, combined with global supply chain disruptions and a limited pool of qualified contractors, contributed to increased pricing. As one interviewee noted: *"Some of them are really gold-plated specifications... We took 80% of the entire world capacity out of the market!"*

While SE promotes cost optimization through lifecycle thinking and early stakeholder engagement, these efforts were challenged by broader market dynamics. High market concentration gave suppliers considerable leverage, which reduced TenneT's flexibility in negotiations. This highlights the importance of aligning SE practices with external economic conditions to enhance cost efficiency.

- **FIDIC Contracts and and contractors readiness**

  TenneT implemented FIDIC Silver Book contracts within a portfolio-based partnership model to manage project risks. This approach placed quality-related responsibilities with contractors, while TenneT retained financial risk. However, integrating SE into this model presented challenges. Contractors needed to adapt their engineering processes significantly, especially in offshore projects where SE practices were less familiar. Many contractors, particularly those from outside the Netherlands, had limited exposure to SE methodologies commonly used in Dutch infrastructure projects.

  Also SE maturity is not a primary criterion during contractor selection, instead emphasis is placed on technical and delivery capabilities. Consequently, some contractors had limited experience with SE, particularly in applying V&V methods. While several acknowledged these gaps and committed to capability development, the transition is ongoing and requires continued support and collaboration.

- **Cultural and Organizational change via SE**

  The cultural and organizational transformation required for successful SE adoption was more extensive than initially anticipated. As new projects and portfolios were launched under tight deadlines, many team members reverted to familiar practices to maintain pace, which impacted consistency and efficiency. This made it difficult to establish a unified SE framework. Although senior management provided strategic support, operational-level adoption was uneven and gradual. Tools, databases, and processes were developed, but more time and effort were needed to embed them into the team's culture. SE implementation goes beyond technical procedures - it requires a mindset shift. For many within the organization and among contractors, this shift is still underway.

  ".....Let's say the attention for the organisational change part, the cultural part and the mindset. there was no time for that." "We kind of run into the fact that there was no time to prepare the people and to make sure the processes were in place before we started to run with them."

- **Program Standardization and Flexibility Constraints** The decision to pursue a harmonized and The decision to standardize across the 2GW program brought operational efficiencies but also introduced limitations in flexibility. In earlier projects like the 700 MW and 900 MW initiatives, contracts could be adjusted more freely. In the current structure, changes to one contract often require alignment across multiple others, making even small adjustments complex and time-consuming.

  "Changing a contract is not difficult... unless you have to align with other parts." This rigidity affects the ability to adapt requirements during execution. Once a requirement is embedded in a shared library, modifying it impacts several projects and contractors. Coordinating these changes can slow progress or create friction. This underscores the need to balance standardization with adaptability in large-scale programs.

10

Discussion

Compared to other sectors, the civil engineering industry has been slower to SE, though it is gradually moving toward a more structured approach to PM. And one of the reasons why integrating SE into project execution remains challenging is that organizations often struggle to fully realize its potential benefits(ProRail et al., 2013). To determine the value of SE, this discussion evaluates the 2GW Program using the framework proposed by Weiss (1972). The starting point is the motivation behind the shift from traditional approaches to SE, triggered by a need for improvement in the infrastructure sector and driven by industrial challenges. By categorizing SE implementation motivations and characterizing the relationships among them, this research reveals the underlying logic for adopting SE in an industry that has been slow to adopt new methods. The discussion then explores three key themes that emerged from the qualitative analysis: requirements management, V&V, and explicit working by digitalization. It considers both the direct and indirect benefits associated with these themes, their current state of implementation, and the gaps and challenges in realizing these benefits (explained comprehensively in figures 10.1, 10.2 and 10.3). Importantly, these themes provide a foundation for evaluating how closely initial SE implementations within organizations align with the expectations set by ISO and INCOSE standards. Where adaptations have occurred, they offer valuable insights into how SE practices are being tailored to meet specific organizational and industry needs, highlighting both the flexibility of SE and the potential for further refinement to fully realize its benefits.

10.1 From Fragmentation to Integration: shift from traditional to SE way of working

In the offshore grid connection industry, as visible from the literature and case study, there is an increased project scale, complexity, and interdependencies. The increasing number of technical interfaces, regulatory requirements, and stakeholder expectations renders traditional PM models increasingly ineffective. Multiple disciplines and interfaces lead to issues of high interoperability and interdependence, and poor long-term knowledge transfer. As evident from the literature study, high interdependencies across components elevate the risk of failure, especially in the absence of centralized mechanisms for alignment and interface control Calvano and John (2004). Hence, there is a need for integrative and iterative approaches in such complex environments, advocating for systems thinking methodologies that go beyond linear models to manage interdependencies and adapt to emerging realities (Brady & Davies, 2014).

From the case study, the need for change emerged in several forms. Firstly, there was an overwhelming increase in project requirements due to scale, technological integration, and new sustainability regulations. Managing diverse stakeholders proved challenging, especially when dealing with conflicting and frequently evolving requirements across the lifecycle (Hubert, 2021). This is echoed in our case study, where interviewees reflect on earlier 700 MW and 900 MW projects, where this leads to fragmented accountability because of multiple owners of requirements. In these earlier projects, reliance on craftsmanship rather than systematic requirement management led to unstructured and static requirements, resulting in poor traceability of requirement origins and misalignment with lifecycle stages. Overreliance on unstructured, document-based methods further exacerbated these issues, creating problems with version control, change tracking, and dependency management. Weak traceability mechanisms and unmanaged requirement evolution are well-documented risks in complex infrastructure projects (Aslaksen et al., 2008; Emes et al., 2012), and Galli (2020) similarly note that inadequate documentation and short-term focus undermine integration effectiveness in large-scale programmes.

Secondly, the absence of a systematic process-based approach meant that requirements were often developed without consideration for the full system lifecycle, leading to unpredictable changes, increased risks, and contractor claims. Without lifecycle considerations, subsystem testing was limited, reducing opportunities for early risk identification and feedback. The case study reflected widespread dissatisfaction with the traditional, sequential, document-heavy development. This linear approach allowed little room for early feedback or iterative system-level prototyping. The absence of early-stage prototyping and testing limits the ability to economically address critical deficiencies once implementation begins (Emes et al., 2012). As deviations from initial designs are common in infrastructure projects, flaws discovered during late-stage subsystem testing often reveal deeper architectural shortcomings that are costly to rectify (Martin, 2004). As noted by Godfrey (1996), early project stages carry the greatest uncertainties, and the decisions made during this period have the largest influence on eventual cost and schedule outcomes. However, in most infrastructural projects, mechanisms for identifying and managing early risks are either weak or entirely absent.

Finally, while the issues could be solved in simpler projects, there is a problem of high resource utilization due to increasing project scale and complexity. As the scale and complexity of the program increases, multiple projects run in parallel as the 2GW takes a program form, and resource shortages become evident. And as the duration of the program is more than 20 years, teams change or rotate between projects, and design decisions, interface logic, and rationale for technical choices are often lost and keep on "reinventing the wheel". The previous setup, which involves redundant review cycles with TenneT working as a quality department for the contractor by reviewing each document, becomes difficult to manage with the limited resources available and could limit consistency and delay project execution (ProRail et al., 2013; Wu et al., 2024).

10.2 Requirement Management – strengthening clarity, traceability, and lifecycle alignment

Implementing a structured requirement management philosophy aligned with SE was aimed at realizing tangible benefits. One of the direct advantages observed is that the adoption of structured, SMART, and functionally-oriented requirements that are consistent with SE principles and supported by tools like Relatics , significantly enhances the clarity and traceability of project requirements, as demonstrated in the case study. The formalization of CRS provides measurable value, particularly in capturing lessons learned and fostering collaboration across business units. As highlighted by ProRail et al. (2013), early stakeholder analysis helps identify conflicting or unrealistic requirements before they escalate into costly issues, thereby reducing late-stage design changes and compliance problems. This proactive approach, often referred to as “left-shifting,” enables early detection and resolution of potential issues. This is especially important because the cost of correcting a requirement error increases substantially the later it is discovered in the development process, with some studies indicating a tenfold increase per phase delay (E. Honour, 2010). Moreover, this structured methodology supports informed early-stage decision-making and facilitates a smoother transition to Operation and Maintenance (O&M) teams. Since CRS are developed from a life cycle perspective, considering the needs of all stakeholders, this reduces post-delivery disputes and technical ambiguities during the operational phase.

As the program progresses and these benefits begin to materialize, it is essential to acknowledge the practical challenges of execution in a dynamic infrastructure environment such as the fast-paced 2GW Program. The rapid expansion from two to fourteen parallel projects, combined with tight tendering deadlines, led to the retrofitting of previously drafted PDF-based requirements that were created before SE practices were adopted into the new SE-based SMART format. This transition was driven more by schedule pressures than by a methodical stakeholder needs elicitation process. Consequently, some requirements were incomplete, contradictory, or overly specific, which introduced inconsistencies and weakened traceability. To fully realize the benefits of SE, it is crucial that requirements meet key quality criteria: they must be unambiguous, complete, consistent, and verifiable to serve as a reliable foundation for system design and validation (SEBoK, 2024). This should be supported by the early deployment of requirements management tools (RMTs), which ensures that teams can focus on defining the content of requirements rather than struggling with tool implementation mid-project (SEBoK, 2024).

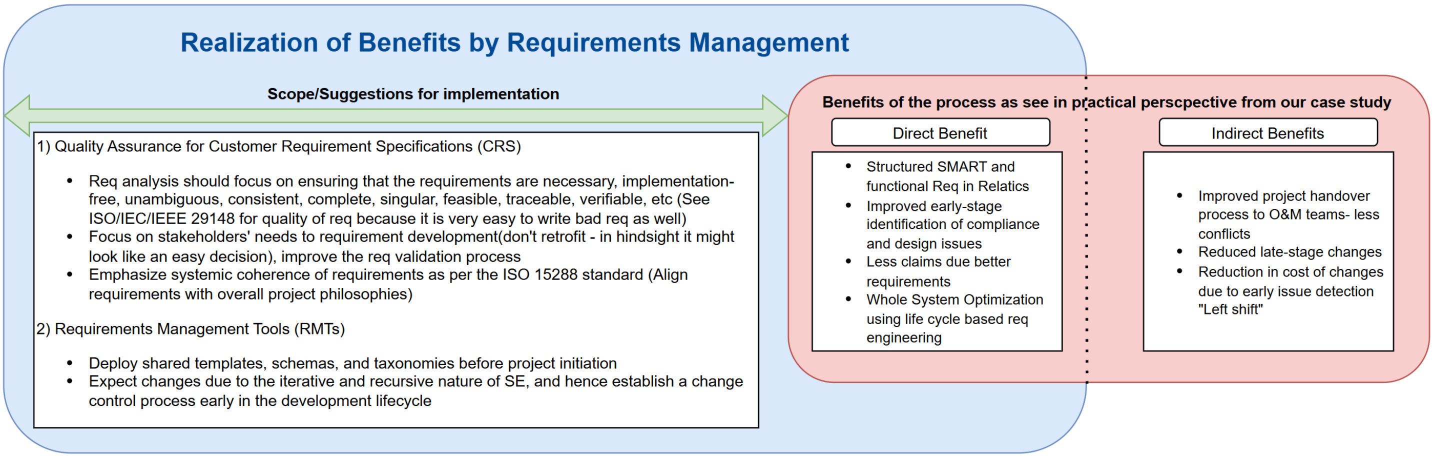

Figure 10.1: Comprehensive view of requirement management discussion

As organizations strive to implement requirement development within a full life cycle perspective, they often face challenges in achieving a unified view. This is particularly evident in the construction sector, where organizational fragmentation such as that described in Section 6.2 means that different departments are responsible for different life cycle phases, complicating the integration of stakeholder inputs. Additionally, it is important for organizations adopting SE to evaluate how SE principles align or conflict with other project philosophies. In the case study, it was necessary to assess how the “standardization and program approach” interacted with SE. As discussed in Section 6.1, standardization was introduced to support scalability and procurement efficiency. However, this approach does not fully align with SE’s iterative and change-oriented nature, which emphasizes flexibility to accommodate evolving needs and requirements. As noted by SEBoK (2024), "due to the iterative and recursive nature of SE across the life cycle there is an expectation of changes to needs and requirements, particularly early in the development life cycle" and lays emphasis on the need for an established change control process early in the projects.

10.3 V&V – ensuring compliance and reducing delivery risks

The structured definition of V&V is -"validation confirms the ’right product is built,’ while verification confirms the ’product is built right.’". The V&V plans encompass clear methods, success criteria, and responsibilities. This approach has been shown to significantly reduce contractual disputes and claims.

By applying a systematic process to the role of V&V, organizations aim to achieve both direct and indirect benefits. With clarified ownership and well-defined compliance checkpoints, project teams can ensure that design outputs are systematically checked against requirements. This reduces ambiguity and improves accountability on both the contractor and client sides. Delegating detailed technical validation to a structured SE framework improves both efficiency and project control. Literature emphasizes that proper V&V of requirements helps ensure that "you are building what the client asks for" (Ark, 2011). This alignment mitigates the risk of delivering misaligned solutions and helps identify potential risks across interfaces and boundaries that might otherwise go undetected in conventional engineering approaches.

Since contractors demonstrate compliance with requirements through V&V, a critical downstream benefit observed is the reduction in rework, particularly in the form of repeated design checks. When SE assumes responsibility for detailed review structures and compliance control, client-side engineers can shift their focus from micro-level verifications to higher-level oversight and governance. This shift not only shortens lead times for document and design reviews but also enhances the utilization of expert resources. However, as emphasized in SEBoK (2024), transferring operational responsibility to contractors does not mean that the client should not maintain the strategic ownership of the process. V&V must begin with the client, starting from the definition of the V&V baseline and expectations. Validation planning, as outlined by INCOSE (2010), should commence as early as the definition of stakeholder needs. Early planning enables the development of validation success criteria, cost and schedule estimation for testing means, and importantly, helps identify unverifiable or ambiguous requirements. This proactive planning is crucial for maximizing the credibility and practicality of downstream validation results (INCOSE, 2010; SEBoK, 2024).

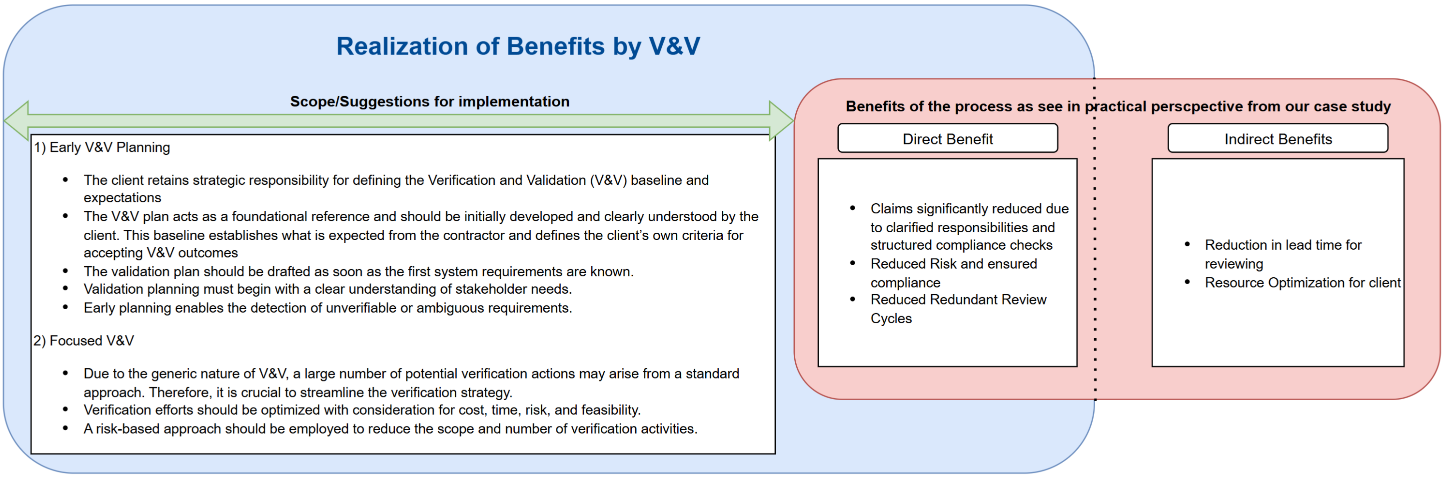

Figure 10.2: Comprehensive view of V&V discussion

Implementing a structured compliance process aligned with the ISO standards is particularly challenging in international offshore projects. One explanation lies in contractor unfamiliarity with explicit V&V expectations. The offshore industry has traditionally followed less formal systems processes and may perceive SE-driven V&V as an administrative burden rather than a core element of engineering assurance. Another challenge stems from the scale and complexity of the 2GW portfolio, where multiple concurrent projects demand a refined V&V strategy that balances comprehensiveness with feasibility. According to SEBoK (2024), it is essential to optimize verification actions by making trade-offs among time, cost, testing practicality, and system risk. Without such an optimization strategy, contractors may become overwhelmed by excessive verification demands, leading to frustration and superficial compliance. Interview insights suggest that this issue is starting to show in practice. Incomplete V&V plans, delays in validation activities, and different interpretations of acceptable results can hinder the realization of full benefits. When validation is removed from contracts or minimized due to pressure or budget constraints, the program becomes vulnerable to gaps that surface late in the lifecycle, often during system acceptance by the operations and maintenance department or during regulatory review. INCOSE (2010) warns against such short-term compromises, stressing that delayed or insufficient validation introduces higher downstream costs and undermines stakeholder confidence.

10.4 Digitalization – enabling traceable, transparent, and integrated delivery

The case analysis highlighted a significant shift from fragmented, project-specific data silos toward a shared, program-level library. This transition enables improved traceability, consistency, and reuse of information across multiple offshore 2GW grid connection projects. It reflects a broader cultural and structural move toward explicit working which is a key principle of the SE approach. It demonstrates the organization's growing maturity in digital practices. This development is strongly aligned with the guidance provided by INCOSE, which emphasizes that SE is fundamentally about managing complexity through architecture-driven decision making, supported by transparent, verifiable models and data repositories (INCOSE, 2010).

ProRail et al. (2013) also supports the fact that such transparency facilitates tracking both technical and managerial decisions over time, allowing stakeholders to understand how system choices and requirements evolve. By grounding communication and decisions in clear documentation, digitalization fosters a shared understanding across disciplines, reducing confusion and helping maintain project alignment. This structured approach to managing and tracing requirements helps in interface coordination, mapping stakeholders needs and system interconnections that in turn accelerate impact assessments when changes occur. As participants noted, this clarity prevents decisions that may appear beneficial in isolation but could negatively affect the overall system. Such transparency ensures that improvements remain aligned with customer expectations and project goals, ultimately delivering better value for money (Ark, 2011). Given that offshore programs often involve multiple actors, the use of common repositories and structured documentation practices ensures that information remains accessible, interpretable, and consistent, regardless of who records or retrieves it, or when. This not only enhances contract management but also safeguards the integrity of shared data throughout the program. Again, this aligns with INCOSE's emphasis on managing complexity through structured, transparent systems (INCOSE, 2010).

However, tool development often occurs in parallel with ongoing project execution, with functionalities being continuously introduced and multiple digital systems integrated. This can lead to interoperability issues and added technical debt. As complexity increases(as seen in the case study), so does the risk of information mismatches, duplicated efforts, and data inconsistencies. This in turn undermines the very traceability that centralized platforms aim to provide. Here, SE principles offer a clear path forward. For any enabling system, such as a program-wide requirements or interface management tool, it is essential to apply the same lifecycle based engineering rigor as is applied to the systems it supports. This includes conducting V&V activities for tool development, ensuring that new functionalities are systematically tested, user needs are captured early, and changes are tracked and reviewed with the same discipline expected of engineering deliverables. Hence, sustaining the realization of benefits requires transitioning from isolated tool creation to development processes driven by stakeholder needs.

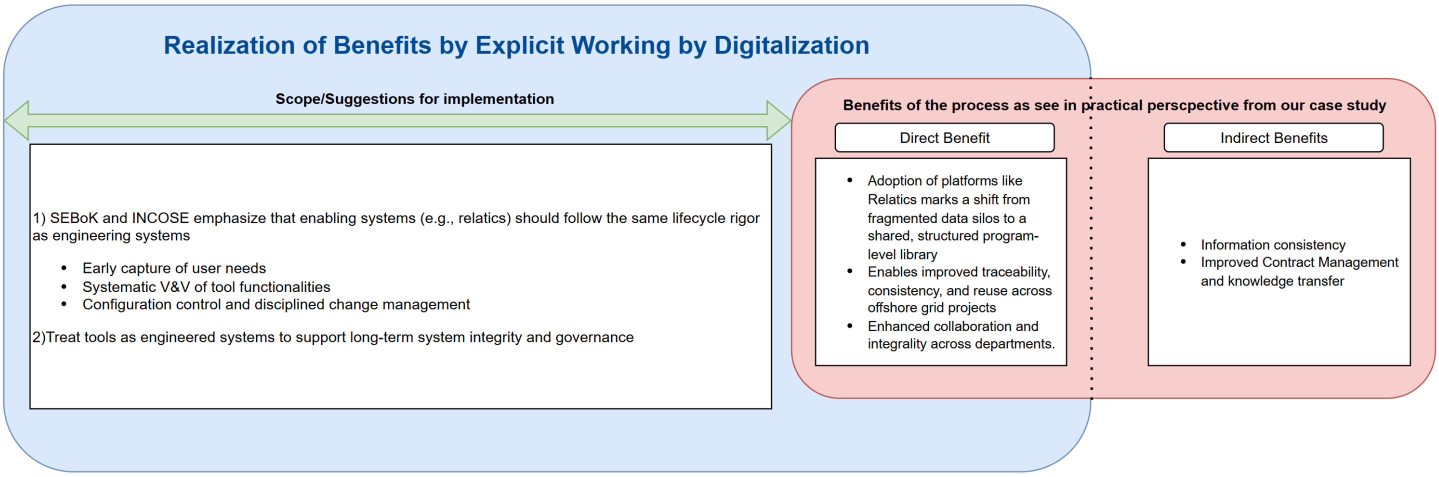

Figure 10.3: Comprehensive view of explicit working discussion

10.5 Generalizability, Research Boundaries, and Future Work

Generalization

While offshore grid development varies significantly across international contexts, this study sought to generate what Thomas (2011) describes as “exemplary knowledge.” Rather than offering a representative or replicable model, exemplary knowledge provides a contextually grounded example: one that resonates with others’ experiences and invites reinterpretation within their own settings. It is through this shifting interpretive horizon that such knowledge becomes meaningful and transferable. The concepts that support the generalizability of the study are:

- Drawing on the lived experiences of practitioners, documentary evidence, and interpretive analysis, this research offers rich, context-specific insights into how SE was understood and adapted within TenneT. The organisation’s unique characteristics– a multi-country operational scope, a strong push for standardisation, and a programmatic approach– shaped the way SE was implemented. By detailing these contextual factors, the study enables other organisations to assess the relevance and applicability of the findings to their own transitions.
- As Stake (2008) emphasizes, the credibility of a case study lies in its continuous triangulation i.e., cross-checking descriptions and interpretations throughout the research process. This study is structured to trace the trajectory from the initial need for SE, through its implementation, to subsequent process improvements, using a major program as the focal case. Each section tries to integrates triangulated evidence to either support or challenge the evolving understanding of the case.

Limitations and scope for future works

The implementation of SE showed a broad spectrum of benefits when thoroughly explored in this research. However the research showed certain limitations which could be explored in future works:

- The client-centric perspective was adopted for this study. Viewing the implementation exclusively from the client’s position tends to emphasize benefits perceived primarily by the client organization. Hence, this perspective might not fully capture the advantages or challenges experienced by contractors, who are instrumental in executing SE principles. The effectiveness of SE implementation significantly depends on the contractors' recognition of its value and their integration of SE practices into their workflows. Further given that most existing literature, including the present case study, predominantly reflects client-side perspectives, there is an inherent bias toward client-recognized benefits. This bias is also evident in studies from the Dutch infrastructure industry, where principal research efforts are led by client organizations such as ProRail and Rijkswaterstaat. To achieve a more comprehensive implementation of SE, future research should integrate contractor insights, facilitating a more balanced understanding of the mutual benefits and practical considerations necessary for successful SE adoption by all involved stakeholders.

- Another limitation could be that due to the constraints of the selected case study and the associated timeline (early stages of the program), this research has primarily concentrated on specific themes i.e., requirement management, V&V and digitalization. Other SE processes, although being implemented, are still at early stages; hence, detailed discussion regarding these additional processes remains limited within this research. Future studies should aim to explore these processes comprehensively at a future stage of the program, thereby enriching the overall understanding of SE's potential benefits.

11

Conclusion

From existing literature, the research has identified a significant gap in understanding the specific benefits of SE and the contextual factors that enable its effective application in complex projects. This study addresses that gap by exploring the lived experiences of practitioners through semi-structured interviews, documentation analysis, and literature review. It seeks to answer the central research question: ***"How can the application of SE address the challenges in offshore grid connection projects and maximize long-term benefits for Transmission System Operators (TSOs)?"*** To address this question, the study is structured around three sub-questions that collectively trace the trajectory from the initial need for SE, through its implementation, to the resulting process improvements. A major program serves as the focal case, providing a practical lens through which the evolution and impact of SE can be examined.

What were the key challenges and problems faced in offshore grid connections projects that necessitate the application of SE?

The initial drivers for adopting SE approach in offshore grid connection projects stem from the diversity and number of stakeholders involved. Government bodies, investors, contractors, environmental groups, local communities, and even departments within the same organization bring their own priorities. As seen in the 2GW Program, such projects face significant challenges due to numerous stakeholder requirements and a wide variety of interfaces. These requirements are often shared among multiple owners, creating transparency and accountability issues. With increasing scale and complexity, multiple projects are executed in parallel, making resource shortages more visible. The lack of a systematic process to verify contractor compliance with requirements often leads to repeated checks and inefficiencies: an issue exacerbated by limited resources. Process-related problems include fragmented lifecycle management, where insufficient early testing and feedback cause design issues to surface at later stages. Offshore projects also face difficulties in managing high uncertainty during early phases, balancing competitive procurement with long-term supplier collaboration, and maintaining delivery schedules under strict climate-related deadlines. The another set of challenges are the technological ones. They arise from high system complexity, integration difficulties, and supply chain constraints. System integration is complicated by multiple disciplines and interfaces, and this is worsened by an unstructured, document-based approach. Such practices result in poor traceability, difficulty managing dependencies, and a lack of clarity regarding the impacts of changes.

What are the expected benefits of SE implementation for TSOs, particularly in the context of offshore grid connection programs?

The implementation of SE within offshore grid connection programs, exemplified by the TenneT 2GW Program is still in its early stages. While institutional commitment to SE is evident, the transition toward fully integrated SE practices is ongoing and incremental. Nevertheless, several anticipated benefits are already beginning to emerge. Based on insights gathered from stakeholder interviews, program documentation, and literature, this section outlines the advantages of SE implementation for TSOs in the context of offshore grid development.

1. **Stakeholder Alignment** - Formalization of CRS enables early identification of conflicting or unrealistic requirements, fostering cross-departmental collaboration and supporting a culture of continuous learning. Structured V&V processes reduce ambiguity and help prevent contractual disputes.

2. **Whole System Optimization** - SE promotes a holistic view of the system under development, often referred to as the "System of Interest." This approach clarifies system boundaries and interfaces, helping to identify and manage interdependencies that might otherwise be overlooked. This supports early scope alignment and better coordination.

3. **Left Shift** - A key ambition of SE is to enable a "left shift" in project activities by addressing potential issues earlier in the lifecycle. Through early-stage requirement management, V&V, and digital modeling, SE reduces the likelihood of costly late-stage changes. By investing in front-end analysis and stakeholder engagement, TSOs can minimize requirement volatility and accelerate testing phases, thereby improving overall project efficiency and reducing risk.

4. **Risk and Rework Minimization** - By ensuring that the requirements match client expectations, SE reduces misalignment and renegotiation. ISO aligned V&V processes streamline reviews and cut rework. Delegating detailed checks to SE frameworks enhances quality assurance and supports the principle of "getting it right the first time."

5. **Enhanced Transparency** - The principle of explicit working which is central to SE, enhances transparency by systematically documenting decisions, requirement changes, and rationale. This helps track technical and managerial choices and supports financial accountability. It also enables effective change impact analysis, ensuring decisions align with project goals.

6. **Complexity Management** - Offshore grid connection projects are inherently complex, often involving multiple phases, contracts, and stakeholders across different geographies. SE provides tools and structured practices based on ISO15288 to manage this complexity.

How have the anticipated benefits of SE been realized in the case study, and what strategies can enhance and sustain these benefits in the future?

The research presents a compelling reference case for offshore grid connection projects initiatives looking to adopt SE to navigate scale, complexity, and cross-sector coordination. As a pioneering effort in offshore grid connection systems, the program not only advances Europe's energy transition but also offers a practical, experience-based lens through which the benefits and constraints of SE can be observed. Importantly, it shows that SE is not a one-size-fits-all solution but a mindset and methodology that must be tailored and incrementally adopted to succeed in dynamic and multi-actor contexts. Key recommendations and strategic insights from the research that can enhance and sustain the benefits in the future are:

1. **Phased Implementation of SE :** Rather than imposing an immediate overhaul, the organization as a client adopted SE in stages i.e., beginning with requirements management and gradually expanding to encompass V&V, configuration management, and traceability. This allowed for organizational learning, iterative tool development, and gradual cultural adoption, a strategy particularly suited to large programs involving actors such as contractors with diverse maturity levels.

2. **Front-Loading Requirements Engineering :** The study shows the critical value of front-loading effort("left shift") in requirements engineering. However:

   (a) Ensure requirement quality and coherence by adhering to ISO/IEC/IEEE 29148 and ISO 15288 standards, focusing on stakeholder needs and aligning requirements with overarching project philosophies like FIDIC contract structures.

   (b) Enhance RMTs by deploying standardized templates and taxonomies early, and establishing a change control process to accommodate the iterative nature of SE.

3. **Early and Focused V&V :** While V&V responsibilities are taken up mostly by contractors, the strategic ownership of V&V must be retained by the client, with clear criteria and traceability mechanisms defined early in the project lifecycle.

   (a) Defining the V&V baseline and expectations acts as a foundational reference for the client's own criteria for accepting V&V outcomes and establishes what is expected from the contractor and defines

   (b) Due to the generic nature of V&V, a large number of potential verification actions may arise from a standard approach. V&V efforts should be optimized with consideration for cost, time, risk, and feasibility.

4. **Engineer the enabling tools :** Digitalization emerged as both an enabler and a challenge. Centralized platforms like Relatics improve traceability and collaboration, but without rigorous governance, simultaneous tool development introduces complexity and technical debt. The insight here is that "SE tools themselves must be engineered with SE principles" i.e., they should be planned, validated, and iteratively improved in sync with user readiness(internal departments) and organizational workflows.

Crucially, the adoption of SE requires more than technical tools; it demands cultural change. As the case study showed that even the best-designed processes falter without broad operational commitment and leadership alignment. SE adoption must therefore be accompanied by intentional change management strategies that promote understanding of the "why" alongside the "how." In conclusion, the study not only illustrates how SE can enhance the execution of complex infrastructure systems but also clarifies the conditions under which these benefits are realized. The case study offers a valuable set of insights and best practices that other public and cross-border infrastructure initiatives can generalize and adapt by emphasizing incremental implementation, early and structured requirements, strategic client-side validation, digital maturity and cultural readiness. By embedding these principles, SE can serve not only as a technical method but as a foundational approach to coordinating complexity and accelerating sustainable transformation.

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A

Appendix - 2GW Philosphy

Standardisation Element	**Description**
One contract model	All 2GW projects are governed by a single contract framework, streamlining legal and administrative processes across the portfolio.
One set of administrative requirements	Project execution is governed by a uniform administrative baseline, reducing fragmentation and misalignment.
One set of technical requirements and designs	Includes the 2GW HVDC platform, 525kV cable system, automation strategy, and cable landstation-ensuring technical uniformity across systems.
Cross-country applicability	Developed standards are valid for both German and Dutch projects, verified against installation locations with only minor adaptations.
Controlled innovation	Design freedom is limited, but innovation is allowed through a controlled process with transparent assessment of impacts on TOTEX and asset performance.

Table A.1: Key Elements of Standardisation in the 2GW Program

Harmonisation Element	**Description**
Comprehensive and coherent specifications	Specifications are structured to meet user needs across all lifecycle phases from development through decommissioning.
Traceability of requirements and decisions	All technical and project related decisions are documented and traceable through structured methods, reducing ambiguity and facilitating audits and change management.
One TenneT execution philosophy	All project activities from design to commissioning are executed in a harmonised, integrated approach across departments, project teams, and countries.
Stakeholder commitment and transparency	Internal and external stakeholders are engaged continuously to ensure alignment, early identification of issues, and joint ownership of outcomes.
Standardised project organisation and management	TenneT applies unified project governance, execution strategies, and operational procedures, facilitating cross border synergies and resource efficiency.

Table A.2: Key Elements of Harmonisation in the 2GW Program

Optimisation Element	**Description**
First Time Right approach	SE ensures that all disciplines work together in a structured, explicit, and traceable way from the start, minimizing design errors and interface mismatches.
Transparent validation and verification	A continuous loop of V&V activities during development, construction, and commissioning supports early detection of issues and evidence-based decision-making.
Database-driven specifications	All project requirements and decisions are maintained in a central specification database using Relatics, ensuring version control, traceability, and a single source of truth.
TOTEX optimisation	All design decisions are assessed against TOTEX . Trade-offs are documented following the SE approach to justify cost-performance balances.
Forecasting and schedule risk analysis	Project milestones are tracked using a statistical schedule risk model to ensure a minimum 70% probability of on-time delivery, enhancing planning reliability.
Knowledge capture and reuse	Lessons learned from previous projects in both Germany and the Netherlands are systematically documented and implemented to avoid recurring issues and promote continuous improvement.

Table A.3: Key Elements of Optimisation in the 2GW Program

B

Appendix - Interview Questionnaire

The complete Interview Guideline that was used is shown below:

- **Introduction**
  - Briefly introduce yourself and your role.
  - Explain the purpose of the interview and the broader research context.
  - Assure confidentiality and explain the use and scope of results.
  - Mention their right to withdraw at any time.
  - Ask for their current role and a brief introduction
  - How long have you been involved in the 2GW program?
- **Theme 1: Key Challenges and Problems in Offshore Grid Connection Projects**
  1. **What have been the key challenges or limitations you've encountered using traditional approaches (business-as-usual) in offshore grid projects?**
     - Could you provide specific examples or critical incidents illustrating these challenges?
     - How have these challenges affected project outcomes?
  2. **What initially motivated TenneT to adopt SE practices?**
     - Was the decision driven primarily by strategic management considerations or operational necessity?
     - Could you describe any specific incidents or situations prompting this decision?
- **Theme 2: Initial Perceived Benefits of SE**
  1. **What were the specific goals and expectations associated with the introduction of SE at TenneT?**
     - Could you define the initial goals from the project or the SE program using the MoSCoW approach (Must-have, Should-have, Could-have, Won't-have)?
     - How clearly were these expectations communicated throughout the organization?
  2. **Since implementing SE, how have you observed immediate changes in people, processes, or technology within your projects?**
     - **People:**
       * Have you noticed an increase in rework or improvement in work efficiency?
       * Are there additional roles or changes in existing roles?

    * Is the integration and communication between departments better now?
    * Are employees adequately skilled to understand and implement SE?
    * Has there been sufficient training provided?
  - **Processes:**
    * How integrated are the SE processes?
    * Is there a common understanding across teams, or is this still developing?
    * Which specific SE processes or philosophies do you believe are most useful to your role or team?
    * Which processes currently add value or are expected to add value, and in what ways?
    * Are there any existing processes you believe should remain unchanged by the SE program?
  - **Technology:**
    * What types of software and technologies were used before the introduction of the SE program?
    * How effective were those technologies?
    * What new software and technologies have been introduced with the SE program?
    * Given the growing digital age, do you believe SE is increasingly useful?

- **Theme 3: Current Status and Challenges of SE**

  1. **Reflecting on your current projects, which anticipated benefits of SE have been successfully realized, and which have yet to materialize?**
     - Could you share examples or specific cases illustrating these realized or unrealized benefits?
  2. **What are the major ongoing challenges or barriers in continuing or enhancing SE practices at TenneT?**
     - Are these challenges primarily related to processes, people, or technology? Please elaborate.
  3. **How consistently are SE principles applied across different phases of your project lifecycle?**
     - Can you highlight any discrepancies between SE theory and its practical application?
  4. **How effective do you find the current level of standardization of SE processes within TenneT?**
     - In your opinion, where is there room for improvement?
  5. **Could you describe how you evaluate and measure the actual and perceivable benefits of applying SE?**
     - Which outcomes mattered most to you and project stakeholders?
     - What criteria or feedback mechanisms are used to assess SE effectiveness?

- **Closing Remarks**

  - Maybe ask for additional comments or insights regarding SE practices and their impacts(only if required).
  - Thank you for your time!! and ask what output matters the most to them.

C

Appendix - Interview Analysis

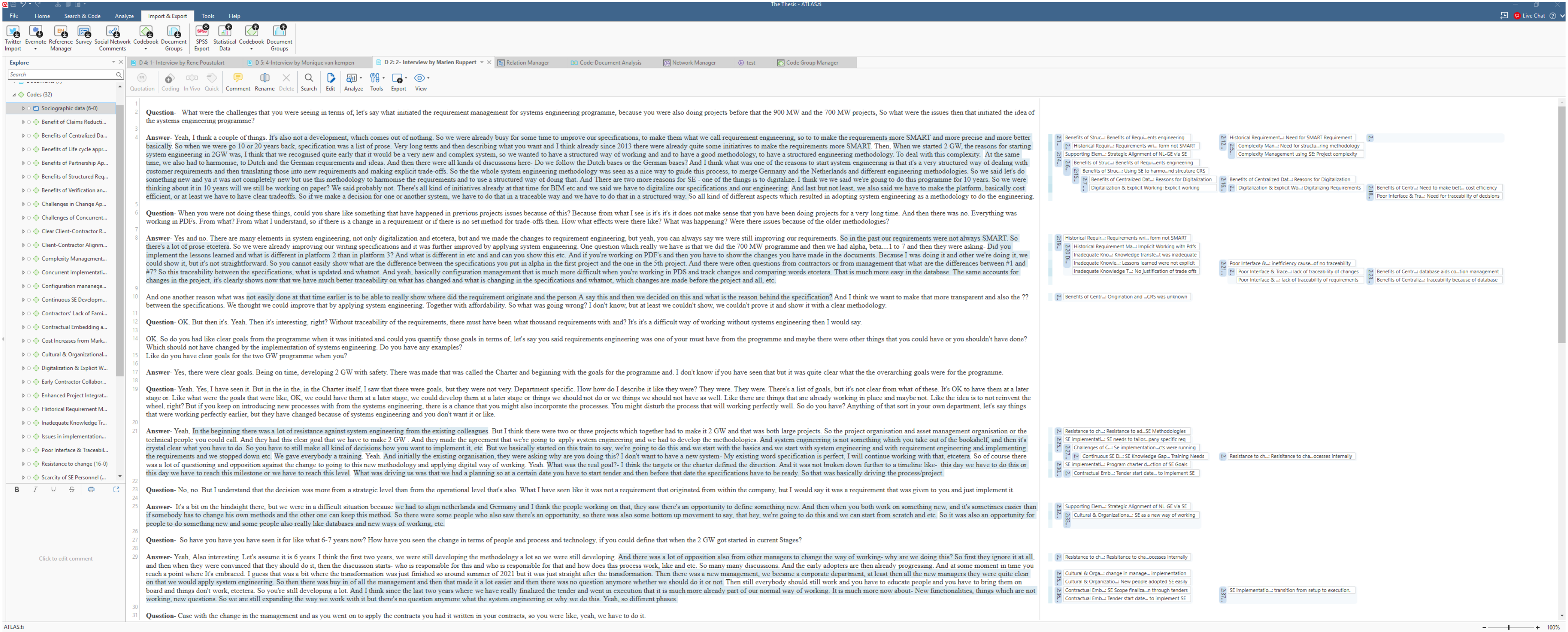

Figure C.1: Example showing 1st cycle of coding

C.1 Codes

Table C.1: Categories and subcodes

Code	
○ **Benefit of Claims Reduction via SE**	
	○ Claim Reduction reasons
	○ Huge claims reduction
	○ Lot of change orders
○ **Benefits of Centralized Database & Traceability**	
	○ database aids configuration management
	○ database aids program integrality
	○ database for logically structured requirements
	○ Need for impact assessment due to change in specifications
	○ Need to make better tradeoffs and cost efficiency
	○ Non uniform data formats for specifications
	○ Origination and reason for a CRS was unknown
	○ Reasons for Digitalization
	○ reduction in time to check for interfaces because of database
	○ traceability because of database
	○ traceability of requirements
	○ transparency in change responsibility and traceability
○ **Benefits of Life cycle approach**	
	○ change in requirements incurs cost
	○ Late changes cost more money
	○ Life cycle approach to make fit for purpose design
	○ Requirements from a life cycle approach
	○ SE ensure smooth handovers to O&M
	○ SE expectation is to reduce changes
	○ Uncertainity management using SE
○ **Benefits of Partnership Approach**	
	○ Contractors benefit because of partnership agreements
	○ Partnership agreements to aid SE
	○ Partnership approach for the whole offshore industry
○ **Benefits of Structured Requirements Engineering**	
	○ Benefits of Requirements engineering

Table C.1 continued from previous page

Code	
	◦ SE Requirement engineering aids standardization
	◦ Using SE to harmonize and strcuture CRS
◦ Benefits of Verification and validation(V&V)	
	◦ requirement verification using V&V
	◦ V&V as quality checks
	◦ V&V as the second SE Methodology
	◦ V&V checks detects issue at earlier design stage
	◦ V&V ensures that the design complies with all req
	◦ V&V reduces risk for contractors
	◦ V&V to ensure compliance with the contracts
	◦ V&V to reduce rechecking
◦ Challenges in Change Approval and Governance	
	◦ Change process
	◦ changes are dificicult due to multiple interfaces
	◦ changes are dificicult due to unknown responsibility
	◦ dependency on other departments to approve change
	◦ Issues with change management process
	◦ Lack of decision in governance of changes
	◦ Multiple stakeholders for a change
◦ Challenges of Concurrent SE Process and tools Development	
	◦ complexity arising from new tools
	◦ Developing Processes and executing at the same time
	◦ Need for more structured processes
	◦ Paradox of new tools developement
	◦ Processes in 2GW as catching a running train
	◦ Requirements developed under time pressure
	◦ Se implementation as projects were running
	◦ Unstructured development of SE related activities
◦ Clear Client-Contractor Responsibilities using V&V	
	◦ Clear client contractor responsibility using V&V
	◦ Clear V&V responsibility reduces workfoce needed

Table C.1 continued from previous page

Code	
	○ Contractor does verification
	○ DEsign and verification is contractors responsibility
	○ Reduce Tennet work to check every document in detail
	○ Reduction in the no of engineering issues
	○ Resources can be reduced as a client
	○ Rework reduction
	○ SE as a tool to discipline company
	○ time reduction due to V&V
	○ Use of SE to give more responsibility
	○ Use of SE to optimize resources
○ Client-Contractor Alignment of Expectations on SE Deliverables	
	○ 4 key processes by Contractors
	○ Client and contractor alignment on SE deliverables
	○ expectation mangement with the contractors for SE Deliverables
	○ Lack of trust in contractor increases rework
	○ Positive outlook for SE
	○ positive response on SE adoption by contractors
	○ quality risk with contractor and financial risk with client
	○ SE processes ensures clear client and contractor responsibilities
	○ SE processes ensures clear client and contractor scope of work
○ Complexity Management using SE	
	○ Need for structured engineering methodology
	○ Project complexity
	○ standardization to reduce complexity
	○ Underestimation of increasing 2GW Complexity
○ Concurrent Implementation in running Projects	
	○ High level of interfaces make database complex to understand
	○ Increased Project compexity
	○ New developments within different projects and portfolios
	○ process implementation in tennet
	○ Processes are developing

Table C.1 continued from previous page

Code
◦ **Configuration mananegement in Tennet**
◦ Configuration management
◦ Easier control of increased complexity using SE processes
◦ easier scalability using functionalities of SE tools
◦ Priority for Safety & O&M Changes
◦ using librariers to manage configuration management complexity
◦ **Continuous SE Development & Learning Curve**
◦ learning curve
◦ Process health checks and maturity
◦ SE as a continuous developement
◦ SE Benefits in longer term
◦ SE Knowledge Gaps & Training Needs
◦ SE Maturity of the organization
◦ workshops to integrate SE understanding
◦ **Contractors' Lack of Familiarity & Resistance to SE Adoption**
◦ Contractors are not familiar with SE Methodologies
◦ contractors dont want to do V&V
◦ Contractors not from Netherlands
◦ Offshore contractors
◦ technology change for contractors
◦ **Contractual Embedding and Scope Definition of SE in Procurement**
◦ Contractual obligation of SE processes by contractors
◦ Realibility on contractors to realize SE Benefits
◦ Reduce the SE Scope aligning with only contractual requirements
◦ Risk division using SE
◦ SE Scope finalization through tenders
◦ Selection criteria of a contractor
◦ Tender start dates as milestone to implement SE
◦ **Cost Increases from Market, Specifications, and Supply Chain**
◦ Changes Driven by Imperfect Requirements
◦ Changing strategies due to political pressures

Table C.1 continued from previous page

Code	
	○ competitive pricing no longer works ○ current 2GW standard specifications are costly ○ Increased cost due to market complexity and limited avaibility ○ Incresed cost due to high quality standard specification ○ Incresed cost due to supply chain problems
○ **Cultural & Organizational Change via SE**	
	○ change in management supported SE implementation ○ Cultural integration of SE way of working ○ cultural reasons for adopting SE ○ Earlier Tennet worked as a quality department ○ Multiple changes along with SE-Concurrent Organizational Changes ○ New people adopted SE easily ○ organizational change with SE ○ SE as a new way of working ○ soft aspect of SE implementation is Imp ○ Time for cultural change
○ **Digitalization & Explicit Working**	
	○ Digitalizing Requirements ○ Explicit working ○ technology change in Tennet
○ **Early Contractor Collaboration (FEED)**	
	○ Collaborated work with contractor in the Early project phases for FEED ○ Early detection of issues because of SE hence reduced costs ○ Front runners in SE who did FEED study first benefited ○ Front-End Engineering Design (FEED) ○ Taking stakeholders needs into CRS ○ Time reduction by early agreements on requirements ○ Time reduction by intiating design in early phases with Life cycle Optimization
○ **Enhanced Project Integration & Internal Collaboration**	
	○ better project integrality ○ Coordination between departments

Table C.1 continued from previous page

Code	
	○ Database for managing Program and project contracts
	○ Easier interaction between departments
	○ Relatics as Common IM Platform
○ **Historical Requirement Management Issues**	
	○ Imperfect requirements lead to additional contract costs
	○ Implicit Working with Pdfs
	○ Issue of specifcations in form of PDFs
	○ Multiple owners for requirements
	○ Mutiple claims due to changing requirements
	○ Need for functional requirements
	○ Need for SMART Requirement
	○ Requirement management as the first SE Methodology
	○ Requirements written in prose form not SMART
○ **Inadequate Knowledge Transfer & Documentation**	
	○ Knowledge transfer between project was inadequate
	○ Lessons learned were not explicit
	○ No justification of trade offs
○ **Issues in implementation**	
	○ Different forms of Validation in Offshore
	○ Inefficiency of SE caused by unclarity on processes
	○ Less flexibility in working
	○ negative response on SE adoption
	○ Poor V&V reports and plans
	○ reduced flexibility due to standardization and harmonization
	○ requirements were not finalized before tender
	○ Still lot of requirements
	○ Tennet expectation based on Dutch industry vs offshore reality
	○ Too many specifications compared to previous projects
	○ V&V loop for design not done
○ **Poor Interface & Traceability Management**	
	○ Impact on req due to change in speification was unknown due to lack of interface

Table C.1 continued from previous page

Code	
	○ inefficiency caused because of no traceability ○ interface management ○ Lack of interface management because of pdfs and multiple owners ○ lack of traceability of changes ○ lack of traceability of requirements ○ Need for traceability of decisions
○ **Resistance to change**	
	○ dislike for V&V due to likeness for technical discussions ○ Initial resistance to change ○ Lack of internalization of SE way of working ○ People go back to old ways of working ○ people prefer not to work explicitly ○ people workaround new processes ○ Resisitance to change existing processes internally ○ Resistance to adopt SE Methodologies ○ Seeing Verification as paperwork ○ Still implicit working
○ **Scarcity of SE Personnel**	
	○ Challenge of finding the right people ○ Lack of SE personnel from Tennet ○ scarcity of labour
○ **SE implementation in tennet**	
	○ First verification strategy in place for Requirements(ERs) ○ Fit for purpose SE development ○ Functioning processes means benefits are realized ○ Phased approach in SE implementation ○ Program charter defined basic direction of SE Goals ○ Projects are on time ○ Realization of SE Benefits takes time ○ SE can aid PM methodologies ○ SE Development on onshore side

Table C.1 continued from previous page

Code	
	○ SE needs to tailored for company specific req
	○ SE processes are not independent
	○ SE working well in Dutch infrastucture industry
	○ Structure of SE roles Developement
	○ Structured way of developing the processes
	○ TERRA Process
	○ transition from setup to execution.
○ **Shift from Project to Program Approach**	
	○ Alignment of SE and Program Goals
	○ Change of working from Project to program approach
	○ Parallel project instead of sequential
○ **Supporting Elements to SE**	
	○ FIDIC contracts supports SE
	○ standardization gives benefits by repitition
	○ standardization to stop reinventing the wheel in every project
	○ Strategic Alignment of NL-GE via SE
○ **Varying SE Maturity and Understanding**	
	○ Different SE maturity in differnet projects
	○ difficulty in understanding SE Value
	○ divided opinions on SE Value
	○ SE understanding Low
	○ Varying maturity of different processes
	○ Varying SE maturity of contractors

C.2 Code Groups

Sr.No	Code Groups
1	Issues that led to SE principles adoption
2	Expected Benefits from SE Implementation
3	Realized Benefits from SE Implementation
4	Current SE program working methodology
5	Challenges faced during Implementation
6	Continuos Improvement measures for SE Implementation
7	External Factors

Figure C.2: Code Groups

D

Appendix - Respondent Validation

D.1 Interview- 1

Interview Title- Realizing Benefits on SE

Interview Date- 15/04/25

Interviewee- Senior Advisor 2GW

Interviewer- Surabhi Agrawal (Master's Student)

1. Requirement Management

- Pre-2GW: Offshore projects (700MW, 900MW) used 2000+ PDF documents with 70+ owners—no structured cross-referencing of changes or interfaces.
- Lack of traceability was a key risk, changes in one document could conflict with others, with no systematic detection.
- SE was initiated to replace this document-based process with a structured, relational requirements database now ~16,000 requirements, providing traceability and structured verification.
- A key success: stakeholder-derived top-level requirements are now much more visible and controlled—preventing late surprises from licensing or external parties.
- Current concern: system has become too complex, too many requirements and too many unnecessary links to BIM and other systems, creating overhead.

2. V&V

- SE was used to clarify responsibility: contractors now must perform verification to show they meet TenneT's requirements.
- Verification is now contractually required; TenneT's role is to check verification files, not to approve designs directly hence reducing risk of claims and project delays.
- This represents a cultural shift: many engineers still prefer to check drawings and calculations, rather than focus on verification files.

- Validation is implied but not the main emphasis; verification is the core contractual tool to ensure quality and accountability.

3. Explicit Working by Digitalization

- SE and the requirements database (Relatics) provide discipline and a clear division of responsibility—contractors own design and verification; TenneT no longer acts as a quality assurance team.
- SE is viewed as an enabler for the overall programmatic goals:
  - Standardization: "Design one, build many" approach to save ~1.5 years per project.
  - Timely delivery: SE's discipline supports fast execution, required by the portfolio timeline.
  - Partnership-based delivery: SE clarifies who does what, enabling more trust-based collaboration with contractors.
- SE is explicitly seen as a means to an end and not the goal itself.

4. Other Direct and Indirect Factors Associated with SE Implementation

- Cultural resistance is significant: many engineers dislike filling in database, following formal verification steps, or surrendering review control.
- German side initially resisted more than Dutch side, but now recognizes value, especially the practicality of having a central database.
- SE has helped in reducing claims and improving the discipline of contractor vs. client roles.
- However, the SE implementation is perceived as too complex:
  - Too many requirements.
  - Over-engineered database architecture.
  - Too many "nice to have" linkages that do not contribute directly to key goals (verification and timely delivery).
- Interviewee recommends refocusing on core principles: clear responsibilities, contractor verification, program priorities and not adding more complexity.
- Current benefits seen: smoother contracting, reduced claims, clearer division of responsibility, better stakeholder alignment, faster execution compared to past models.
- Belief: SE is essential, without it, portfolio delivery would not be feasible within required timelines.

D.2 Interview- 2

Interview Title- Realizing Benefits on SE

Interview Date- 18/04/25

Interviewee- Head of Asset Management Offshore development

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. Requirement Management

- Before SE, requirements were long prose documents, not SMART, making it difficult to track changes or show how lessons learned were applied across projects.
- Traceability and configuration management were key drivers for adopting SE: prior projects (e.g., 700MW) lacked clear documentation on how and why requirements evolved between versions.
- Harmonization of Dutch and German engineering practices was another key reason to adopt SE; SE's structured approach helped bridge these differing methodologies.
- There was early resistance from existing teams who were used to traditional Word specifications, but phased adoption, training, and management buy-in gradually overcame this.

2. V&V

- Contractors (especially Dutch civil contractors and oil & gas firms) were generally supportive of SE; some German contractors had lower initial maturity.
- The verification process was implemented later, and now as execution progresses, contractors sometimes misunderstand or inconsistently apply SE expectations.
- Verification is now explicit and traceable (checkmarks, reports), whereas in the past it was implicit; this shift still faces mixed acceptance (approx. 50% of users see clear value).

3. Explicit Working by Digitalization

- SE and Relatics-based digitalization have proven critical for scaling the program: managing 70 billion euros worth of 14 parallel projects would not be feasible otherwise.
- Now, SE has enabled much better traceability of changes, their origins, and rationale—improving the ability to manage complexity as the program scaled from 2 to 14 projects.
- The library-based configuration management across projects in the program is seen as complex and successful approach, pushing the limits of the current tool performance.
- Shared tools (Relatics) and shared SE methodology have improved cross-department collaboration (e.g., Asset Management and PMO), enabling more integration and transparency.
- The process maturity is still developing: core basics are in place, but new functionalities and processes (e.g., risk management) are still being integrated.
- SE also forced explicit roles and responsibilities—improving accountability across departments.

4. Other Direct and Indirect Factors Associated with SE Implementation

- The basic SE processes are well established: requirement engineering, system breakdowns, trade-offs, and verification.

- Scaling the program was one of the biggest success stories: SE and digitalization made managing the complexity feasible.
- Without SE, managing version control, traceability, and requirements across such a large and fast-growing program would have been unmanageable.
- Adoption journey: initial resistance, followed by buy-in after transformation (~2021), and now SE is embedded in the standard way of working.
- Some inefficiencies and complaints arise from teething problems: unclear requirements, immature/developing processes, and learning curves on both TenneT and contractor sides.
- Challenges remain in harmonizing change processes and ensuring process clarity—but SE provided the foundation for improving this further.
- SE was also adopted as an opportunity to align Dutch and German practices on neutral ground, rather than one side "winning."

D.3 Interview- 3

It was seen as a sample interview.

D.4 Interview- 4

Interview Title- Realizing Benefits on SE

Interview Date- 28/04/25

Interviewee- Lead Project Management 1

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. Requirement Management

- SE was introduced to move from wordy, non-SMART specifications toward structured, functional requirements that enable verification.
- Initial contracts reused text-heavy 900MW German project specs, which were reworked into SE-style requirements over ~2 years.
- 30,000+ requirements now exist—many still non-functional, ambiguous, duplicate, contradictory—driving a high number of changes during execution.
- Current change process is slow and difficult because harmonization and standardization require alignment across multiple projects/portfolios and stakeholders, limiting flexibility.
- SE has improved transparency of requirement issues: changes are now more visible and traceable, but content quality is still lacking.
- Root causes include time pressure, insufficient preparation, and lack of clear rationale behind many requirements .

2. V&V

- Verification is contractually mandated, but validation was negotiated out.
- Contractors must perform requirement analysis workshops and provide verification reports—but progress is slow and quality is still poor.
- SE was introduced to reduce TenneT resource load by making contractors responsible for verification—this shift of responsibility is not fully realized due to contractor gaps and internal hesitance to strictly enforce SE.
- SE's potential benefits (avoiding rework, reducing risk, ensuring compliance) are hindered by contractor immaturity in SE and internal inconsistency in enforcing SE requirements.
- The benefit of SE is clear in ensuring contractors can prove compliance, reducing the risk of late rework and disputes—but execution maturity is still low.
- Final design payments are conditional on V&V—but in reality, if delays would threaten project timelines/costs, enforcement is often compromised.

3. Explicit Working by Digitalization

- SE tools like Relatics and processes (e.g., requirement analysis workshops) have improved visibility, traceability, and consistency across projects.
- SE supports the design one, build many strategy by creating a structured base for reuse—but misaligned requirements and late changes risk undermining this goal.
- Digitalization has also made requirement issues and ownership more visible—some blame SE for this, but SE only revealed pre-existing weaknesses.

4. Other Direct and Indirect Factors Associated with SE Implementation

- Standardization, not SE itself, is driving many current difficulties (e.g., inflexibility in handling changes across projects).
- Contractors' lack of SE maturity was underestimated—many had no prior experience and now must restructure their engineering approach, causing delays.
- Management focus and cultural readiness were insufficient: too many changes were introduced simultaneously (new contracts, SE, digitalization, new ways of working), overwhelming the organization and contractors.
- SE was not fully supported by program-level leadership; stronger pressure on contractors was needed to ensure proper SE adoption.
- Some key benefits are emerging (e.g., better understanding of compliance, fewer surprises during review), but current reliance is still too low to replace traditional engineering review practices.
- Soft side of SE (culture, mindset, change management) was neglected—this remains the main barrier to realizing SE's full potential.
- Interviewee stresses: people are open to change, but not to massive change all at once; future SE success depends on phased adoption and stronger leadership support.

D.5 Interview- 5

Interview Title- Realizing Benefits on SE

Interview Date- 30/04/25

Interviewee- SE Advisor

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. Requirement Management

- Initially, requirements were non-SMART, highly detailed, solution-oriented, and spread across multiple documents, often inconsistently.
- SE was introduced with a primary early focus on requirements engineering: restructuring, improving, and digitalizing requirements into a single database.
- Moving from document-based to database-based management required changes in thinking and responsibilities, as requirements could now apply across multiple systems.
- Due to project time pressure, the initial database and specifications were not fully complete when tenders began; updates continued during tender and contract execution phases.

2. V&V

- Contractors initially resisted V&V processes, viewing them as extra work.
- Verification is still an active area of effort; validation is recognized as essential (especially for ensuring stakeholder needs are met and for smooth handovers), but is not yet fully embedded.
- Many internal reviewers still distrust contractor V&V, choosing to read documents end-to-end rather than relying on provided verification reports.
- SE aims to shift this mindset toward targeted, trust-based checking that would free up reviewer capacity for higher-value tasks.
- There is recognition that proper V&V is key to achieving SE benefits and preventing operational issues post-handover.

3. Explicit Working by Digitalization

- The requirement database (Relatics) and the creation of a program-wide library support baseline control, tracking of deviations, and reusability.
- The database now supports baseline management for partnerships and framework agreements, tracking deviations per contractor/project, and enabling reuse for future projects—an important efficiency gain.
- The change process, however, is a major unresolved issue: lack of clear governance on who can authorize changes (program level, asset management, or project level) has led to changes "floating" in the system.

- The phased SE rollout started with requirements engineering; V&V processes were added during contract preparation, but full SE maturity is not yet reached.

4. Other Direct and Indirect Factors Associated with SE Implementation

- SE was strategically introduced to manage increasing complexity, project concurrency, and the shift to partnership-based contracting.
- The energy transition urgency and program growth created strong time pressure, forcing parallel development of SE processes and project delivery—preparation time was lacking.
- The rapid scaling of projects, growing team size, and continuous adjustments required for the evolving program outpaced the readiness of SE processes and tooling.
- Organizational change and cultural adoption were underestimated: many staff still default to prior ways of working, and there was insufficient time and effort invested in mindset shift and training.
- Contractor SE maturity varies greatly: some contractors improving, others still resisting or unable to demonstrate explicit compliance.
- Learning from Rijkswaterstaat's phased, multi-year SE adoption suggests that time and cultural adaptation are essential; SE success is a long-term investment (benefits expected to become clearer in later projects).
- Despite current gaps, SE has already improved visibility, traceability, and requirements control—without it, managing today's 2GW program complexity would be untenable.
- Continuous improvement is built into the SE strategy, recognizing that maturity will build progressively across projects.

D.6 Interview- 6

Interview Title- Realizing Benefits on SE

Interview Date- 01/05/25

Interviewee- Lead Project Management Office

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. Requirement Management

- Previous projects used hundreds of pages of prose text for requirements; teams lacked certainty about requirement fulfillment.
- Introduction of database driven requirement management (Relatics) aimed to enable change management, verification loops, and traceability.
- Now requirements are explicit, traceable, and verifiable and this is seen as already improving quality and reducing ambiguity for engineers.

- However, initial requirements were not top-down; started from mid-level instead of deriving from end customer/system goals, it is seen as a missed opportunity.
- Incomplete clarity of initial requirements still leads to costly changes later, which SE could have prevented if fully adopted from the start.

2. V&V

- Verification reports are helping engineers focus on what to check and what not to check, improving review efficiency and clarity.
- Some project teams still fail to enforce SE expectations with contractors and if V&V reports are not delivered and teams don't ask, then compliance is weak.
- Contractor responses are mixed: some are improving, others claim to be compliant but cannot demonstrate it when asked.
- If handover occurs without full V&V, risk shifts to TenneT—interviewee is clear they would not accept such a handover personally.

3. Explicit Working by Digitalization

- Relatics is in use and providing benefits, particularly in requirements traceability and preparing for scaling/reuse across future projects.
- Full benefits expected when SE allows for reuse of verified designs with minimal rework, though projects are still too early-stage for this to fully materialize.
- Configuration management is still a weak spot - seen as a key process needing urgent improvement to avoid future chaos in managing changes.
- Interviewee sees potential to expand SE mindset to other domains (risk management, audit tracking), but organization is not ready yet.

4. Other Direct and Indirect Factors Associated with SE Implementation

- SE was strategically driven: initiated at corporate level to address project complexity, not from grassroots demand.
- Cultural barriers remain: experts feel loss of influence/power when SE enforces explicit, requirement-based reviews rather than expertise-driven ones.
- SE's transparency and accountability can feel threatening to both internal staff and contractors, reducing enthusiasm for adoption.
- Lack of lifecycle-wide SE ownership: Operations/Maintenance departments do not yet use SE or Relatics, though this could evolve once 2GW assets go live.
- SE seen as indispensable despite challenges as without it, current project complexity would risk major failures.
- Future success depends on corporate-wide SE alignment and consistent application across the full project lifecycle—this is currently missing.
- Measuring SE benefits remains difficult; aims include reducing rework, reducing change lead time, and improving review efficiency, but data to make historical comparisons is lacking.

D.7 Interview- 7

Interview Title- Realizing Benefits on SE

Interview Date- 05/05/25

Interviewee- Lead 2GW Program Office (DE)

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. V&V

- SE vision includes moving verification responsibility to contractors to reduce TenneT's internal review effort.
- However, this shift has not been fully accepted: German-side projects are not actively applying SE as intended; Dutch side shows partial application, often driven by more mature civil partners.
- There is a perception of risk: internal experts fear they are being asked to trust contractor validation without sufficient ability to influence or oversee the design.
- Without consistent application of SE processes (especially verification), future warranty and maintenance disputes are expected, as poor documentation and unclear ownership of verification will resurface in post-delivery issues.

2. Explicit Working by Digitalization

- Relatics implementation was delayed; early project phases did not use it, and SE processes were not ready when projects launched.
- Now some projects resisted switching to SE/Relatics mid-stream to avoid disruption.
- Cultural resistance is also present: SE seen as extra work, needing more capacity (which is lacking)
- Some civil contractors are better positioned with SE due to prior experience, but widespread adoption across portfolios is minimal—especially on the German side.

3. Other Direct and Indirect Factors Associated with SE Implementation

- Current perception is that there is a disconnect between the SE framework requirements and actual practice—projects continue to use older, ad-hoc methods.
- Delays in SE rollout (Relatics not ready from project start, training late) meant projects defaulted to previous ways of working; trying to introduce SE mid-project now risks claims of delay or disruption from contractors.
- The "design 1, build many" intent of SE is seen as valuable for future projects, but current inconsistency will limit synergy and standardization gains unless SE is adopted more uniformly.
- Cultural resistance is significant: many experienced staff feel SE reduces their ability to influence design but leaves them exposed to risk if outcomes fail.

- SE rollout suffered from lack of early management buy-in and insufficient staffing (SE advisors added late).
- There is a misalignment between contract obligations (SE in framework) and project realities—while SE is contractually required, current project pressures deprioritize it.
- In Long-term, interviewee believes SE would deliver workload reduction and quality gains by standardizing and reducing rework, but current short-term focus on delivery is undermining adoption.
- Positive change would require strong management push and clear communication that SE investment now will benefit the program over 2nd–6th projects.
- Without consistent early adoption, synergy across projects will not materialize, and each project may continue to struggle individually.

D.8 Interview- 8

Interview Title- Realizing Benefits on SE

Interview Date- 06/05/25

Interviewee- Lead Project Management 2

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. Requirement Management

- Initial requirement analysis was not completed before contract signing, causing late discovery of requirements even a year after project start.
- Older contracts lacked specificity; SE helped create clearer, traceable requirements (e.g. from "visible color" to "platform should be yellow").
- Now requirements are mapped and traceable in Relatics, but gaps still exist — not all requirements are complete or correct.

2. V&V

- Verification emerged as the most beneficial SE process: contractors now assign verification methods and moments to each of 12,500+ employer requirements (In the given portfolio).
- Validation practices were partly present before SE but lacked formal alignment with SE processes.
- Current model reviews and BIM reviews act as validation, though terminology and perception gaps remain.
- Contractor transitioned from outdated Access-based systems to adopting Relatics mid-project — a risky but courageous move to strengthen verification processes.

3. Explicit Working by Digitalization

- TenneT's own Relatics tools are functional and provide a digital backbone for requirement traceability and verification workflows.
- Configuration management remains inefficient, with document-based change tracking still in use limiting efficiency.
- Contractors' digital readiness is uneven: while some are upgrading systems, execution phase verification (especially in locations like Singapore yards) still faces challenges, requiring increased inspection efforts.
- Offshore industry was largely new to SE and lacked in-house expertise; contractors had to scramble to find resources and often misunderstood SE scope initially (e.g. mistaking it for an IT standard).

4. Other Direct and Indirect Factors Associated with SE Implementation

- A key driver for SE adoption was the need to manage multiple parallel projects with limited employer-side resources hence shifting quality responsibility to contractors.
- Contractor maturity varies , while some (e.g. IV) adapted early through FEED studies; others faced steep learning curves.
- SE implementation is closely related with contractual structures (e.g. FIDIC Silver), making it difficult to isolate the benefits purely attributable to SE.
- Cultural change is gradual: while "early adopters" at both TenneT and contractor side understand SE, hearts and minds in traditional engineering teams are slower to shift.
- Standardization vs. SE: While SE aims to optimize design, extensive standardization (design once, build many) limits flexibility for further improvements and creates a tension between innovation and repeatability.
- Training alone is insufficient to get the expected benefits. Real progress comes from sustained dialogue, active management pressure, and contractual enforcement (e.g. withholding payments for non-compliance).

D.9 Interview- 9

Interview Title- Realizing Benefits on SE

Interview Date- 07/05/25

Interviewee- SE Manager GSC

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Meeting Notes

Introduction and Role

The interviewee is a SE Manager at TenneT, with experience in SE and project control in the Dutch construction sector. He joined TenneT in 2020, during which IV was finalizing the FEED for the 2GW program (initially started in 2019). His role involves tailoring SE processes and tools to fit TenneT's organizational needs.

Focus Areas

Roughly 60% of his work focuses on contractors and 40% on internal TenneT teams. For contractors, his role includes managing expectations, reviewing deliverables, and supporting process improvement. Within TenneT, he works on training staff in SE methodology and the application of FIDIC contract principles.

His work is closely tied to five key SE processes: configuration management, verification, validation, requirements engineering, and technical query handling.

Challenges in SE Implementation

One major challenge was that SE processes were not in place from the start of the program. This led to process development during project execution, creating inefficiencies. The lack of proper tooling, limited resources, and unclear stakeholder roles further contributed to delays—especially in configuration management.

Currently, process maturity has improved, although tool development is still ongoing. Stakeholder awareness and process adoption are now a key focus.

Reflections and Observations

He emphasized that early "impact analysis of methodology" could have helped in better structuring SE efforts. The late development of processes reduced the perceived value of SE. Although SE is supported under the FIDIC Silver Book, contractors still need a clearer understanding of its benefits.

People and Process Issues

There is a shortage of senior professionals to guide mid- and junior-level staff. SE advisors are designing good processes, but without sector-specific experience, these often face challenges in application. Also, SE knowledge is still siloed and not broadly distributed.

Process development has been reactive rather than need-driven. For effective process design, ownership, purpose, scope, and stakeholder clarity must be defined. He recommends using maturity models (e.g., CMMI) or frameworks like Plan–Do–Check–Act.

Tool Integration and SE Value

Tools such as 3D models and Relatics exist but are not well integrated. Improved interface between tools is necessary. He noted that SE benefits will only be realized if tools and processes are fully functional, regularly reviewed, and integrated with project controls like WBS/SBS and cost/time tracking.

D.10 Interview- 10

Interview Title- Realizing Benefits on SE

Interview Date- 08/05/25

Interviewee- Sub project lead project Management

Interviewer- Surabhi Agrawal (Master's Student)

Recording Method- Audio recording

1. Requirement Management

- The primary role of TenneT's SE team in offshore projects is to specify clear, SMART employer requirements at the front end, without directly developing the design. Initially, projects used vague, prose-heavy documents; now they use structured, traceable requirements with unique IDs, reducing ambiguity and improving traceability.
- Current contracts (e.g. FIDIC Silver Book) are very detailed, with ~10,000–15,000 requirements per substation. Contractors are required to demonstrate compliance with these requirements through verification reports, shifting the effort of demonstrating compliance from TenneT to the contractor.
- This explicit requirement specification has improved clarity, reduced ambiguity, and lowered potential for late-stage rework.

2. Verification and Validation

- Verification is the main focus for contractors, with explicit expectations to provide verification plans and evidence of compliance.
- Validation is not formally contractually required(in the given portfolio) but occurs in practice through interactions and reviews (e.g. design reviews, clarifications). The team intentionally avoided overburdening contractors by requiring full formal validation early on.
- Contractors' capability in SE varies. Dutch contractors are more mature; others (UAE, Germany, Asia) require education and support. A phased approach (starting with verification, adding validation later) was seen as more effective.

3. Explicit Working by Digitalization

- The evolution of SE tools (e.g. Relatics) from basic requirement databases to a complex architecture enables traceability and integration across contracts.
- However, the current digital landscape has become overly complex and difficult to manage ("spaghetti monster"), with lack of initial vision and proper SE methodology in the software development itself.
- There is room for improvement in aligning software development with SE principles (traceability, verification/validation), stakeholder engagement, and project needs.

4. Other Direct and Indirect Factors Associated with SE Implementation

- Change management remains a challenge: complexity arises due to accountability splits between Asset Management (AMT) and LPO (execution), especially when lessons-learned trigger changes post-contract.

- SE was introduced to improve clarity and reduce ambiguity, not necessarily to reduce resource use — although “design one, build many” benefits from the program approach are expected to yield resource efficiencies.
- Human factors: The organization has grown; specialists now collaborate on verification reports instead of solely reviewing documents. Successful implementation depends on tailoring SE processes to market maturity and project timelines.
- Lessons: Avoid "over-asking" contractors, adopt stepwise SE maturity development, and align SE scope with project and contractor capabilities.

D.11 Interview- 11

Interview Title- Realizing Benefits on SE

Interview Date- 15/05/25

Interviewee- Lead Project Execution

Interviewer- Surabhi Agrawal (Master’s Student)

Recording Method- Audio recording

1. **Requirement Management**

- Started by rewriting requirements to be clearer, smarter, and database-driven to support structured requirement engineering.
- Requirements originate from Asset Management, with reviews conducted together with O&M to ensure alignment with operational needs.
- Traceability is partially implemented: ownership of each requirement is recorded, but reviews are not yet fully stored within the database.
- Change management is evolving for requirement changes are logged with reasons for traceability, supporting continuous learning and improvement.

2. **V&V**

- A core goal of SE implementation is to ensure that each requirement is verified by contractors and tracked for internal acceptance and future handover.
- Verification helps avoid disputes at handover by providing documented proof of what was specified and delivered.
- Current V&V practices are still maturing: Some processes (e.g. overly granular Inspection and Test Plans) are seen as administratively heavy and are under review.
- Contractors face adaptation challenges in applying explicit verification, though this is progressing.

3. **Explicit Working by Digitalization**

- The shift to database-driven requirement management represents a key digitalization milestone i.e, a move away from paper-based practices.
- The database enables better transparency, traceability, and ease of communication:
  - Requirements are now easily referenced (no more "searching through a book").
  - Communication with contractors is more focused and efficient.
- Digital tools support continuous learning: change histories and reasons are logged, facilitating lessons learned for future projects.

4. **Other Direct and Indirect Factors Associated with SE Implementation**

- Resource optimization is a major driver: "doing more with fewer people" to cope with peak project loads and future pipeline stability.
- The use of SE helps compensate for limited human resources by ensuring structured processes and reusable strategies across portfolios.
- Change of personnel remains a challenge; evolving interpretations of requirements due to staff turnover have led to inconsistencies.
- Cultural and process adaptation is ongoing