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Conceptual Modeling for Architectural Reasoning in the Energy Domain

University of South-Eastern Norway
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A PhD dissertation in
Nautical operations

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Dedication

To my children, Eilev and Torje.

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Kongsberg, Norway, 2022

Abstract

This thesis explores systems architecting in the concept stage in the energy domain. Specifically, the thesis explores how conceptual modeling can be applied in this context to support architectural reasoning. The main focus is on supporting the systems architecting process in the industrial setting when evolving mature systems designs.

In the last decade, the energy industry has been through significant changes, demanding drastic cost reductions and increasing the need for collaboration across the actors in the industry. The changes have led to increasing complexity, both in terms of the technical system and regarding business and organization. Coping with the increasing complexity requires the engineers to improve their systems awareness and balance conflicting needs in the early phase of system development.

Within other industrial domains, the literature proposes using conceptual modeling in the early phase of system development to support concept exploration and knowledge sharing. Several case studies from the energy domain have shown the potential of applying conceptual modeling to support the challenges the energy industry is facing. Still, there is low adoption of such approaches in the industry. The approaches must be adapted to the specific needs of the energy industry to increase the industry's adaption.

The thesis presents the results from four-year longitudinal research in a system supplier company in the energy domain. The research presented in the thesis is conducted under an Industrial Ph.D. scheme. The candidate has been employed in the company of research before and during the research.

The thesis is article-based and consists of five appended articles. Through several studies in the company of research, we have explored how conceptual models can support architectural reasoning in the concept stage. The appended articles present the findings from the studies in the company of research.

Article 1 and Article 2 present results from the exploration of the current practice in the early phase of system development in the company of research. The studies revealed a need for improving the engineer's awareness of the context of the system. Further, the studies identified an opportunity to use conceptual modeling to improve systems awareness. Article 3 presents an in-depth study from the company of research to understand the challenges and needs for improving systems awareness. The article also presents four aspects to improve practitioners' likelihood of adopting a new approach. Article 4 presents a case study applying conceptual models to support reasoning in the early-phase concept evaluation. Article 5 synthesizes the insights from this case study in Article 4 and the insights gained throughout the research and proposes an approach for using conceptual modeling to support system-level decision-making. Finally, Article 5 evaluates the approach in an industrial setting and evaluates how it supports the challenges and needs identified in Article 3.

This thesis contributes to the Systems Engineering Body of knowledge by providing insight into the challenges in current systems engineering practice in the energy domain and the industry needs in the concept phase. Further, the thesis contributes with insight into the application of conceptual modeling in an industrial setting. Finally, the research contributes with a practical approach, guiding practitioners in applying conceptual models in their daily work.

Key words: Systems Engineering, Systems Architecting, architectural reasoning, conceptual modeling, systems awareness, system-level decision-making, energy domain

List of Articles

Article 1

Engen S, Falk K. (2018). Application of a System Engineering Framework to the Subsea Front-End Engineering study. INCOSE International Symposium 2018. 28(1), 79-95. doi:10.1002/j.2334-5837.2018.00469.x

Article 2

Engen S, Falk K, Muller G. (2019) Architectural reasoning in the conceptual phase - a case study in the oil and gas industry. 14th Annual Conference of System of Systems Engineering (SoSE), 87-92. doi:10.1109/SYSOSE.2019.8753863

Article 3

Engen S, Falk K, Muller G. (2021) The Need for Systems Awareness to Support Early-Phase Decision-Making - A Study from the Norwegian Energy Industry. Systems. 2021, 9(3). doi:10.3390/systems9030047

Article 4

Engen S, Falk K, Muller G. (2021) Conceptual Models to Support Reasoning in Early Phase Concept Evaluation - a Subsea Case Study. 16th International Conference of System of Systems Engineering (SoSE), 95-101. doi:10.1109/SOSE52739.2021.9497467

Article 5

Engen S, Muller G, Falk K. Conceptual Modeling to support System-Level Decision-Making - A Longitudinal Case Study from the Norwegian Energy Industry, Submitted

Supporting Articles

Article 6

Engen S, Mansouri M, Muller G. (2019) Application of system thinking to frame the problem in a subsea development projects with high-level business requirements. 14th Annual Conference of System of Systems Engineering (SoSE), 87-92. doi:10.1109/SYSOSE.2019.8753863

Article 7

Helle K, Engen S, Falk K. (2020) Towards Systemic Handling of Requirements in the Oil and Gas Industry – a Case Study. INCOSE International Symposium, 30(1), 1-17. doi:10.1002/j.2334-5837.2020.00704.x

Article 8

Haugland R, Engen S. (2021) Application of A3 Architecture Overviews in Subsea Front-End Engineering Studies: A Case Study. INCOSE International Symposium, 30(1), 495–509. doi:10.1002/j.2334-5837.2021.00850.x

Other Publications

Falk, K, Ulsvik OK, Engen S, Syverud E (2019) Systems Engineering Principles to Enable Supplier-Led Solutions, Offshore Technology Conference, Houston, Texas, May 2019. DOI: https://doi.org/10.4043/29403-MS

Myhre S, Engen S, Falk K. (2020) Transferring Needs and Operational Experience from Life-of-Field to Engineering functions - a case study from the Subsea Industry. INCOSE International Symposium. Vol 30, 95-101. doi:10.1002/ j.2334-5837.2020.00788.x

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Table of Key Concepts

The list below presents some key concepts used throughout the thesis, including a description of how we define them within this research.

Architectural reasoning……………………………………………………………………………22,54

The process of developing and reasoning about the systems architecture.

Conceptual Models……………………………………………………………………28, 32, 60, 66

Models that are sufficiently simplified to help architects to understand, reason, communicate and make decisions, (Muller, 2015b).

Concept……………………………………………………………………………………12, 23, 31, 52, 60

An abstraction of an alternative system solution.

Concept evaluation……………………………………………………………………………31, 52, 60

Evaluation of which concept best fulfills the system's objective.

Decision-Making…………………………………………………………………22, 25, 30, 57, 60, 66

The process of generating alternatives, evaluating them, and choosing the most suitable concept

Key Drivers……………………………………………………………………………………54, 57, 60, 66

The most essential objectives for a group of stakeholders, e.g., customer key driver, business key driver.

System…………………………………………………………………………………………………….17

A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not, Dori et al. (2020) .

Systems Architecture……………………………………………………………………………………..21, 23

An abstract representation of the system, defining the system structure and behavior. The systems architecture defines the form, what the system is, and the function, that the system does.

Systems Architecting……………………………………………………………………………21, 54, 57, 66

The process of defining the system architecture. Systems architecting is the creation and building of a system and supports exploring the system's needs and design.

System Awareness……………………………………………………………………………………………57, 66

Awareness of the system in its operational context, the encompassing systems, and the system's role in a larger system of system.

System Context……………………………………………………………………………………….…18, 57, 66

The environment the system operates in. The system context includes everything outside the system that interacts with the system.

Tension……54, 60, 66

Conflicts or disagreements on which concept best fulfill the system's objective.

1 Introduction

This thesis explores systems architecting in the concept stage in the energy domain. Specifically, the thesis explores how conceptual modeling can be applied in this context to support architectural reasoning. The main focus is on supporting the systems architecting process in the industrial setting when evolving mature systems designs.

In the last decade, the energy industry has been through significant changes, demanding drastic cost reductions and increasing the need for collaboration across the actors in the industry. The changes have led to increasing complexity, both in terms of the technical system and regarding business and organization. To evolve successful systems in the new market, companies need to utilize existing systems knowledge effectively.

Systems architecting supports engineers in understanding complex systems, designing and managing them, and providing long-term rationality of decisions made early in the project (Crawley et al., 2004). The process of developing the systems architecture is called architectural reasoning. Our research focuses on how conceptual modeling can support engineers in architectural reasoning. The research builds on the work of (Borches, 2010; Haveman, 2015; Heemels & Muller, 2006), which all have evaluated conceptual models in an industrial setting to support systems development. The primary outcome of the thesis is learnings of how conceptual modeling can be used in the industrial setting in the energy domain to support engineers in reasoning and communicating during early phase decision making and concept evaluation.

This chapter presents the research background, gaps, objectives, and questions. Finally, the chapter presents the company of research and outlines the remaining of the thesis.

1.1 Research Background and Context

The Norwegian energy industry is a high-tech industry, delivering systems and services to the global market. The first discovery of oil and gas on the Norwegian continental shelf occurred at Ekofisk in 1969 (Norwegian Petroleum, 2021). Since the start of oil and gas production in 1971, the energy industry has contributed significantly to Norwegian wealth. From 2000 to 2014, the industry had its golden age, and the incomes from the sector contributed to 12% of the country's gross domestic product (Ssb.no, 2017). The industry developed a high volume of fields in this period, and the oil companies and suppliers experienced economic growth. In this period, the cost level increased rapidly, and for the subsea deliveries, the cost tripled in the period 2005-2013. The increase in cost was significant compared to the activity increase (OG21, 2015). In 2014 the industry experienced a downturn, as there was a significant price drop in the Brent oil. With the drop in the oil price, it became challenging to develop profitable fields (Bergli & Falk, 2017). The low oil prices set requirements for the whole energy industry to develop more effective solutions in a challenging market (Garcia et al., 2016)

The energy industry is looking towards systems engineering to cope with the challenging market situation. In 2016 the International Council of Systems Engineering (INCOSE) established the oil and gas working group (INCOSE, 2016). The working group's goal was to strengthen the oil and gas industry by applying systems engineering methods. In the mission, the working group emphasizes the importance of the companies adopting new ways of working as the industry is faced with ever more diverse environments, necessitating each company to adapt rapidly. Although the industry is in the frontline of developing high-tech systems, its maturity of systems engineering application is low compared to other high-tech industries such as automotive and defense (Helle, Engen and Falk, 2020). Reasons why the industry is lagging include that it has not been necessary due to the good market situation, focus on tailor-made designs, and conservative company cultures.

Through the industry master program in systems engineering at the University of South-Eastern Norway, master's students have researched the application of systems engineering approaches in the industry (Falk & Muller, 2019). Muller and Falk (2018) used some of these cases to illustrate what Systems Engineering can contribute to the oil and gas industry. They found that oil and gas is a complex domain that may benefit from methods and techniques that have been beneficial in other domains. Systems Engineering methods and techniques applied in industrial setting through this research include (among others); Pugh matrix and concept evaluation(Lønmo & Muller, 2014; G. Muller et al., 2011; Solli & Muller, 2016), A3 Architectural Overviews (Boge & Falk, 2019; Frøvold et al., 2017; Haugland & Engen, 2021; Løndal & Falk, 2018; Muller et al., 2015), Illustrative Concept of Operations (Aarsheim et al., 2020; Solli & Muller, 2016) and conceptual modeling (Bryn & Muller, 2017; Henanger et al., 2016; Muller et al., 2015). Most of the case studies find great potential for applying systems engineerings methods and techniques in the industry. However, the cases also show challenges related to implementation and adoption in the industry (Løndal & Falk, 2018). Muller and Falk (2018) highlighted the need for studies with a longer duration to understand the longer-term effects and impact on the organization.

1.2 Research Gaps

Although research from the industrial context has shown great potential to apply systems engineering methods and techniques to support the oil and gas industry, it is still a challenge of adoption in the industrial setting. Muller and Falk (2018) highlighted that the oil and gas industry should adapt the methods and techniques to their setting and needs to benefit from systems engineering.

The Norwegian subsea industry is increasingly applying systems engineering processes to ensure their projects' success (Mjånes, Haskins & Piciaccia, 2012). Wee and Muller (2016) stated that the subsea supplier companies typically use a project execution model built on the Vee model. In (Engen & Falk, 2018), we evaluated the systems engineering process in the early phase of systems development in the company of research. By comparing the existing company process to Sols' Systems Engineering Framework (Sols, 2014), we identified the shortcomings and potential improvements in the current company process. The study showed a lack of consideration of other stakeholders than the client and a poor understanding of the needs in the early phase. The challenge is not unique to the company of research. In (Tranøy & Muller, 2014), the authors analyzed cost overruns in another subsea supplier company. They found that the primary reason for cost overruns was the poor identification of operational needs during the early phase.

Furthermore, our study showed that the changing market condition required the supplier companies to work differently in the concept studies. Earlier, the company mainly had described the concept proposed by the client in their studies. However, with the changing market, it was expected that the company would take more responsibility for developing concepts (Engen & Falk, 2018). Taking greater responsibility for the concept development requires the suppliers to be more aware of the context of the systems (Engen, Mansouri & Muller, 2019)

In the early phase of the systems life cycle, the engineers explore concepts and make design decisions. The decisions made in this phase define most of the system design and realization and decide most of the systems' value, cost, and risk (Gonzales, 2018; Maier, 2019). Thus, making appropriate design decisions is key to making the system development viable since the cost of change becomes increasingly expensive as the system design matures (Honour, 2014). The main reasons for poor design choices in the early phase of multi-disciplinary development include lack of a cross-functional language, poor communication, and ineffective knowledge sharing (Bonnema et al., 2010; Borches, 2010; Boucher & Houlihan, 2008; Heemels & Muller, 2006; Tomiyama et al., 2007). Heemels and Muller (2006) also highlighted the challenge that design choices are based on experience and intuition rather than quantitative arguments.

To support efficient evaluation of design choices over multiple disciplines, Heemels and Muller (2006) proposed the Boderc design methodology for high-tech systems. The Boderc design methodology is intended for use in an industrial setting and focuses on utilizing the existing domain knowledge in the evaluation. The methodology focuses on identifying and quantifying tensions to select the critical design aspects. Further, the authors proposed using models and measurements to elaborate on the critical aspects. Based on experience from modeling in the industry, Heemels and Muller highlighted that the model should be easy to build and have a reasonably accurate predictive power. Borches (2010) proposed the A3 Architectural Overviews (A3AO) to make the domain knowledge explicit. The A3AO intends to support the communication of architectural knowledge across disciplines and stakeholders in multi-disciplinary projects. A strength of A3AO is visual models to represent systems information, as it communicates to a diverse group of stakeholders. Havemann (2015) built on the A3AO and proposed linking the structural views to an operational view exploring the system's behavior. In his work, he proposed a method to communicate the behavior of systems (COMBOS), to communicate the outcome from modeling and simulations across stakeholders. He highlights the importance of visualizing the operational views to reason about the system behavior from different perspectives to facilitate multidisciplinary design discussion.

In (Engen, Falk & Muller, 2019), we explored the challenges of multi-disciplinary systems development projects in the company of research. The study explored the work practice and the tools and techniques used in the problem exploration. The study showed the importance of co-located multi-disciplinary teams but highlighted the lack of tools to effectively communicate and capture systems knowledge. Further, the study found that the engineers struggled to quantify the issues and made their system-level design decisions based on intuition rather than facts. Heemels and Muller (2006) found that modeling and simulations could support engineers in such quantification. Cases from applications in the industry have shown that conceptual models and visualization support the communication and decision making in the subsea industry (Muller, Wee & Moberg, 2015; Solli & Muller, 2016; Løndal & Falk, 2018).

1.3 Research Objective and Questions

The research clarification revealed a need to improve the systems engineer's awareness of the encompassing system. Further, we found an opportunity to use conceptual modeling to improve systems awareness and support architectural reasoning in the concept study. Consequently, we define the following objective for this thesis:

- Understand the industry needs to improve the awareness of the system in the early phase of system development
- Support practitioners in the energy domain in applying conceptual models in daily work to improve architectural reasoning.

To address these objectives, the thesis focus on the following research questions:

RQ1: What are the challenges and needs for improving systems awareness in the early phase of system development in the subsea industry?

a) *How aware are system engineers of the encompassing system and the operational context of their system during the early phase?*
b) *What are the barriers to exploring and understanding the system and operational context in the early phase?*
c) *Which aspects are important to consider when developing and implementing approaches to improve systems awareness in the early phase?*

In order to answer RQ1, we did a qualitative study in the company of research. Through seven semi-structured interviews, a survey with 126 respondents, observation, and technical documentation review, the study analyzed the system engineer's awareness of the system context and the current barriers to improving this awareness. Further, we used the findings from our study and a literature study to identify the aspects to consider when proposing systems engineering approaches for the energy industry. These questions are mainly answered by Article 3, supported by the findings in Article 1, Article 2, and supporting Article 6.

RQ2: How can conceptual models support the early phase of system development in the subsea industry?

a) How can conceptual models improve the system awareness of the engineers in the early phase?
b) How could an approach for using conceptual modeling to support system-level decision-making in the energy industry look?

To answer this RQ, we have applied conceptual models in several cases in the company of research, as presented in Article 4, Article 5, and supporting Article 7. In addition, in the interactions with practitioners in the industry, we have seen how they respond to conceptual modeling and explored what is needed to support them in applying models. Finally, we have used the learnings from these interactions to outline an approach to support the application of conceptual modeling in daily work. Articles 4 and 5 answers these research questions.

RQ3: How applicable is an approach for conceptual modeling for the early phase of system development in the subsea industry?

a) How do the engineers perceive the usefulness of the approach?
b) What are the challenges for the engineers to adopt the approach in the industrial setting?

Finally, to answer RQ3 and understand how applicable the proposed approach is in the industrial setting, we performed a qualitative study in the company of research. Through a survey with 37 participants, we evaluated how the systems engineers perceived the approach's usefulness. From the survey result, we extracted the challenges related to implementation in an industrial setting. This research question is answered by Article 5.

1.4 Company of Research

We have conducted the research in the company TechnipFMC. TechnipFMC is a global leader in the energy industry, providing technology to the traditional and new energies industry (TechnipFMC, 2022). The company delivers fully integrated projects, products, and services. The company has more than 20,000 employees located in more than 40 countries worldwide. Our research focuses on the Norwegian branch of the company, with approximately 1,200 employees, mainly delivering integrated subsea systems.

1.5 Thesis Structure

The thesis consists of 8 chapters. This chapter (Chapter 1) introduces the research, describing the research problem, goal, and research question.

Chapter 2 introduces the subsea field development to familiarize the readers with the research context.

Chapter 3 presents the literature background of the thesis to familiarize the readers with the topics, including systems engineering, systems architecting, decision-making, and conceptual modeling.

Chapter 4 presents the research methodology applied and the reasoning for selecting the given approaches. The chapter also presents the methods of data collection used in the thesis and the approach used to evaluate the validity of the research.

Chapter 5 presents a summary of the appended articles and collects the main results from the research.

Chapter 6 synthesizes the result presented in Chapter 5 and relates the findings to the frame of reference presented in Chapter 3.

Chapter 7 gives an overall evaluation of the validity of the research, using the approach described in Section 4.5

Chapter 8 presents the research's overall conclusion, evaluates the thesis results in relation to the research goals and questions, and discusses the work's industrial and academic contributions.

2 An Introduction to the Subsea Field Development

2.1 The Subsea Field Development Process

Our research focuses on the development of subsea oil and gas fields. Figure 1 illustrates an actual field development on the Norwegian continental shelf. The green areas are the reservoirs of oil and gas, which can be located several thousand meters beneath the seabed. The subsea system consists of the subsea structures and the flowlines on the seabed and the riser connecting the subsea structures to the topside facility. On the surface is the topside facility, which could be an offshore rig or a ship.

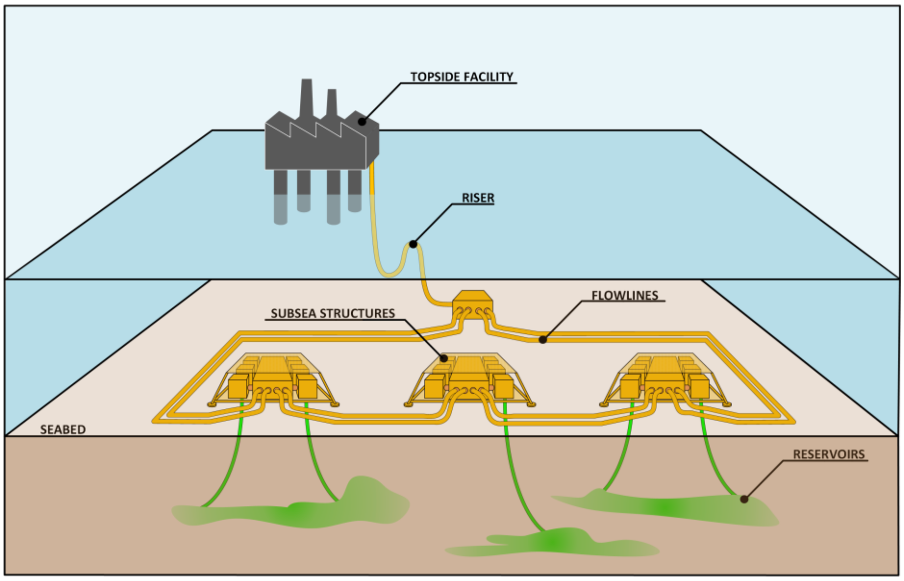

Figure 1: Illustration of a subsea field development

In Norwegian territory, the authorities are the landowners of the entire continental shelf. In areas where the Authority has opened for petroleum activity, they grant production licenses to interested parties. The authority typically issues the licenses to an energy company or a consortium of companies. Further, the authority designates one of the companies that receive the license as the operator for the field development, that is, the *field operator*.

After receiving the license, the field operator starts the field development process, shown in blue in Figure 2. The first phase is the exploration phase, where the operator starts exploration drilling to locate trapped oil or gas in a reservoir beneath the seabed. When they have discovered oil or gas, the operator performs detailed geological and economic evaluations to decide if the field is viable to develop or not. If the field operator decides to develop, they conduct reservoir simulations to optimize the field development scenario and suggest the number and location for the initial wells.

Next, the field development moves into a feasibility phase, in which the operator starts exploring the concepts they can use to realize the field. Following the feasibility phase, they further mature the concepts in the concept phase. Then, in the Front-End Engineering and Design (FEED) phase, they plan the project and perform a basic design for the selected concept. Following is the detail and constructions phase before the system goes into the operation phase.

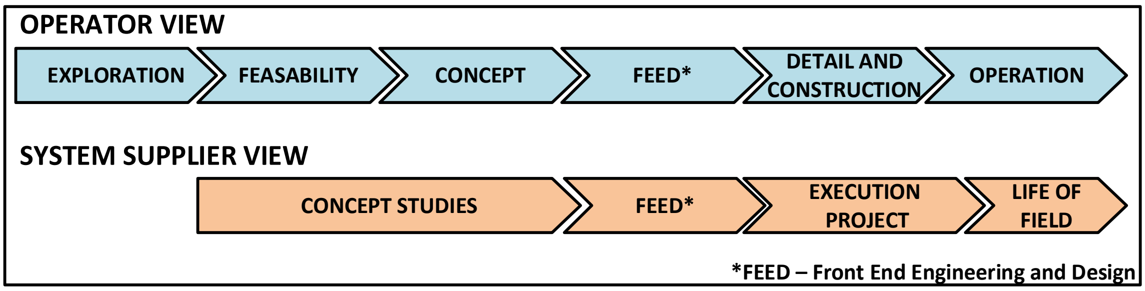

Figure 2: Field development process (Article 5 © 2022 TBA)

In the feasibility and concept phase, the operator split the scope of the field development into several systems, one of them being the subsea system. The process shown in orange in Figure 2 shows the field development process from the system supplier view. Their process starts in the feasibility phase when the field operator invites companies such as the company of research to propose concepts for realizing the field. The concept studies' time frames are often relatively short, from weeks to a few months, with many iterations as the concepts mature. Since several suppliers compete for the same contract, they must develop a system concept that covers the field operators' needs and is competitive in costs. At the same time, the suppliers must ensure that the concepts are also profitable and fit into the company's strategy and portfolio of systems.

Following the concept studies phase is the Front-End Engineering Design (FEED) phase, where the suppliers tender the system, committing to cost and schedule. The study and FEED phases end with a contract award, where one of the subsea systems suppliers will get a contract for the scope. The contract type in the Norwegian oil and gas industry is Engineering, Procurement, Construction, and Installation (EPCI) contracts, meaning that the supplier awarded the contract will get the full scope for the subsea system (O. A. Engen et al., 2018). After the contract award, the supplier will execute the project, carrying out the engineering, procurement, fabrication, and installation. Once the supplier has installed the system at the field location, they hand over responsibility to the field operator. In addition, the supplier gives technical support such as maintenance and repair in the operational phase.

2.2 The Subsea Systems

This section briefly introduces the subsea system to clarify the terms used throughout the thesis. In the research, the system is the subsea production system the supplier company delivers to the field development. The subsea system consists of several subsystems. Each subsystem is typically treated as a work package in studies and project execution. The subsystems consist of components. Figure 3(a) shows the relation between the system, subsystem, and component. The subsea system is a part of a field development, that is, the system of systems. Figure 3(b) illustrates the subsea system as part of the field development. It also shows other systems that are part of the field development, including but not limited to the topside facility, legacy subsea system, drilling rig, installation, and pipe-lay vessels.

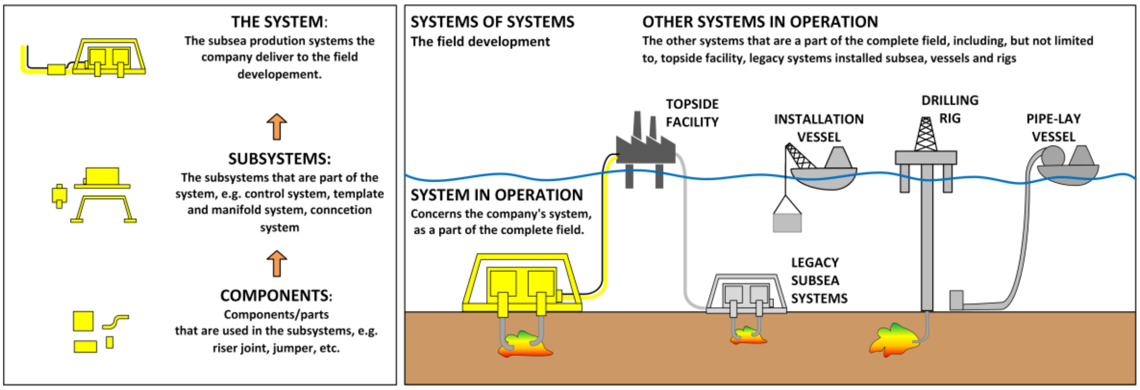

Figure 3: (a) Relation and definition of the system, subsystems, and components. (b) Relation and definition of the super system (Article 3)

Figure 4 shows the subsystems of the subsea system as discussed in the thesis. The system consists of the subsea production system (SPS) and subsea umbilical, risers, and flowlines (SURF). The SPS is located at the seabed and interfaces with the well. The SURF system brings fluids and signals between the SPS and the topside facility. Between the SPS and SURF systems are a tie-in and connection system. Table 4 presents a short description of the subsystems shown in Figure 4.

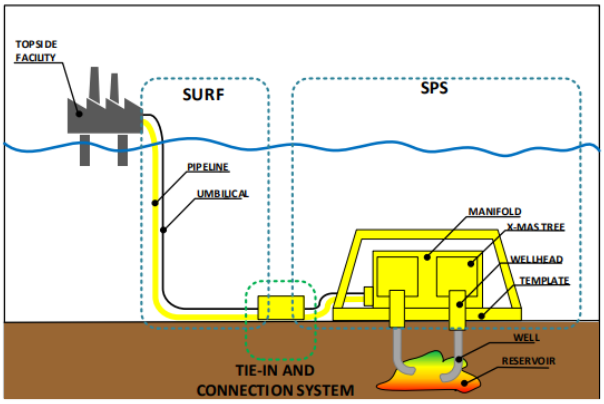

Figure 4: Overview of the subsea system (Supporting Article 8 © 2021 INCOSE)

Figure 4 shows the subsea system as only one template and manifold structure, with a simple infrastructure to the topside facility. However, the field development will consist of several template structures, with an extensive infrastructure of flowlines and umbilicals in real life. Figure 5 gives a more realistic illustration of an actual field layout. Interested readers can refer to Leffler, Pattarozzi & Sterling (2011) for more information on oil and gas field developments.

Table 1: Subsea system descriptions, adapted from Article 4 and Article 5

System	Description
Wellhead (WH)	The wellhead is a pressure-containing interface between the well and the X-mas tree.
X-mas Tree (XT)	The Xmas tree acts as a pressure barrier between the well and the environment, controlling the flow of oil and gas from the well. The XT includes a control module to control the valves on the tree and downhole and collect signals from the manifold and topside/onshore facilities. Depending on the valve arrangement, an XT is either a Horizontal X-mas Tree (HXT) or a Vertical X-mas Tree (VXT).
Manifold	Manifolds collect, handle, and distribute production fluids from several wells. The manifold also includes a control module to control the manifold valves and collect sensor information.
Template	A template is a structure that provides a foundation for the subsea equipment. For an on-template system, the manifold, XT, and wellhead are installed on the template. For the off-template system, the well is located outside a template. The wellhead and the XT are installed at the well and tied back to the manifold.
Umbilical	An umbilical supplies electrical signals, chemicals, and hydraulic services between subsea equipment and the topside/ onshore facility.
Flowlines	Flowlines transport the production from the subsea production system to the topside/onshore facility.

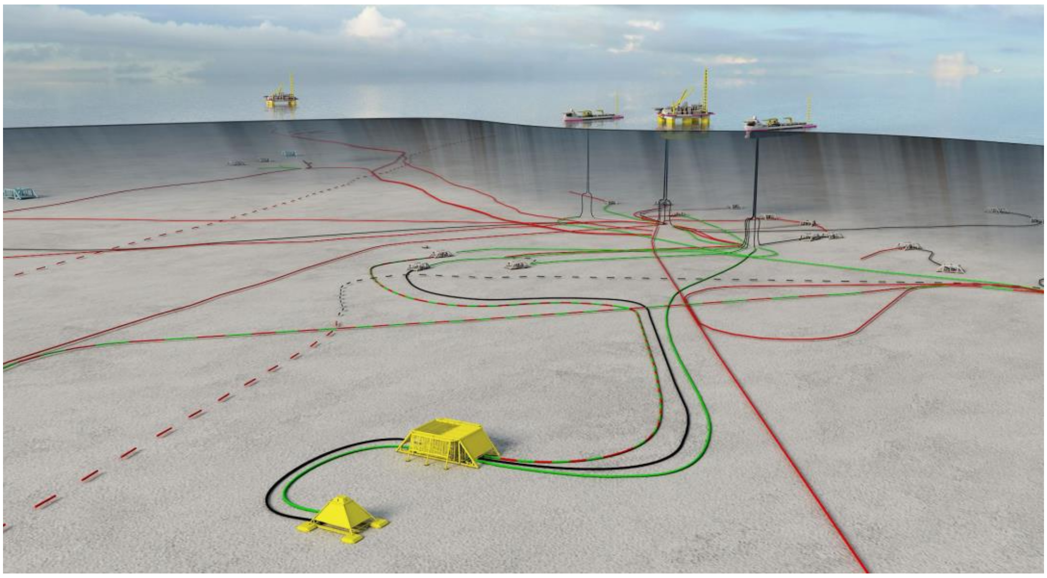

Figure 5: Illustration of the subsea system in operation (© 2022 Equinor)

3 Frame of Reference

This chapter presents the theoretical background for the research presented in this thesis. We position the thesis within systems engineering, focusing on systems architecting. We first present literature on systems engineering and systems architecting to introduce the terms and aspects considered throughout the thesis. Following, we present literature specifically on the concept stage of system development and the challenges in multi-disciplinary system development. Next, we present literature on decision-making, existing frameworks for systems architecting decisions, and literature on decision-making methods applied in the industrial setting. The following section reviews the literature on conceptual modeling, presenting different views on the term conceptual models in the literature, and states how we define this within our research. Finally, we present literature on applying systems engineering in the energy industry, focusing on decision-making and conceptual modeling.

3.1 Systems Engineering

3.1.1 Introduction

We base our definition of systems engineering on the work of the International Council of Systems Engineering (INCOSE). They define systems engineering as follows:

"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.

We use the terms "engineering" and "engineered" in their widest sense: "the action of working artfully to bring something about." "Engineered systems" may be composed of *any or all of people, products, services, information, processes, and natural elements"* (Sillitto et al., 2019).

Blanchard and Fabrycky (2011, p. 17) defined a system as *"a set of interrelated components functioning together toward some common objective(s) and purposes(s).*" Further, they stated that a system is composed of *components, attributes,* and *relationships*. Significant aspects of any system are structure and behavior. Crawley, Cameron, and Silva (2016) denoted these aspects as *form* – what the system is and *fit* – what the system does. Dori et al. (2020) stated that behavior is the most important aspect of human-made systems as it enables the system's function, which in turn provides expected value. Further, they proposed a new definition of the system, recognizing the importance of the behavior; *A system is an arrangement of parts or elements that together exhibit behavior or meaning that the individual constituents do not.*

All systems operate in an environment. The system environment may be broadly defined as everything outside of the system that interacts with the system (Kossiakoff et al., 2011, p. 51). When developing systems, awareness of the context and the system's role in a larger capability is essential (Dahmann & Baldwin, 2011). Buede (2009, p. 50) defined systems external systems as a *"set of entities that interact with the system via the system's external interfaces"* and system context as a *"set of entities that can impact the system but cannot be impacted by the system."* Figure 6 illustrates this relationship.

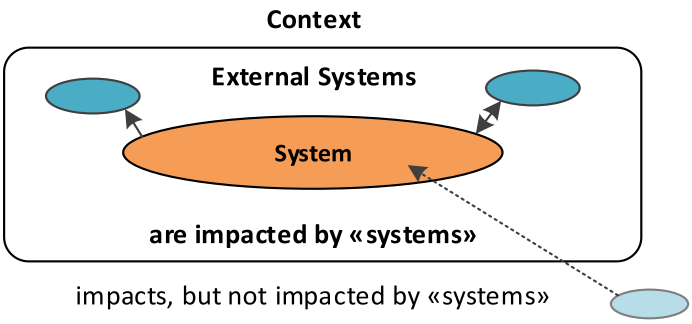

Figure 6: Relation of the system, external system, and context, adapted from (Buede, 2009, p. 50)

Gharajedaghi (2011) stated that *"no problem or solution is valid free of context."* He introduced *openness* as one of the system principles to define a system's characteristics. To evaluate openness, he defined three boundaries; *control* – the part of the system we to some extent can control, *influence*, the part we cannot control but only influence, also called the transactional environment, and *appreciate*¸ the environment the system is operating in that we cannot control or influence, the contextual environment.

3.1.2 Systems Life Cycle Models

A fundamental concept of systems engineering is that *"all systems are associated with a life cycle"* (Blanchard & Fabrycky, 2011). The system life cycle starts with a need and ends with the system phase-out or retirement. Figure 7 shows the generic systems life cycle stages according to (ISO/IEC/IEEE 15288, 2015).

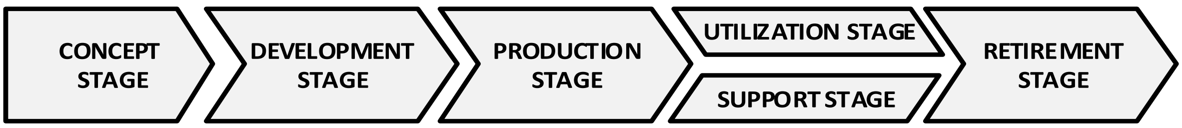

Figure 7 The life-cycle stages of a system, adapted from (ISO/IEC/IEEE 15288, 2015)

Table 2 gives an overview of the main activity in each life-cycle stage, adapted from (INCOSE, 2015, p. 28; ISO/IEC/IEEE 15288, 2015).

Table 2: Main activity in the generic life-cycle stages, adapted from (INCOSE, 2015, p. 28; ISO/IEC/IEEE 15288, 2015)

Life-cycle stage	Type of resources
Concept	Define problem and solution space
	Identify stakeholder needs
	Explore feasible concepts and propose viable solutions
Development	Define and refine system requirement
	Create a description of architecture and design
	Implement initial system
	Integrate, verify, and validate the system
Production	Produce systems
	Inspect and verify
Utilization	Operate system to satisfy users' needs
Support	Provide sustained system capability
Retirement	Store, archive, or dispose of the system

Even though the life-cycle stages are described as linear, iteration and recursion will occur between the phases, and the activities constituting these stages can be interdependent, overlapping, and concurrent (INCOSE, 2015). Consequently, a project should not follow a predetermined set of activities or processes unless they add value toward achieving the final goal.

3.1.3 Systems Engineering Processes

A typical process for system engineering is the Vee Model (Forsberg & Mooz, 1991). According to (INCOSE 2015), the Vee model is *"a sequential method used to visualize varying key areas for the systems engineering focus, particularly during the concept and development stages."* The Vee model focuses on validating the stakeholder needs during the development phases and on the need for verification plans. Other systems engineering processes include the Waterfall and Spiral models (Blanchard & Fabrycky, 2011, pp. 50–51).

Sols (2014) proposed a System Engineering Framework whose intention is to allow the transformation of identified needs or opportunities into a solution. He emphasized that this is a framework and not a process. He claimed that using the term process indicates linearity in executing a series of steps, which offers little latitude or flexibility. In contrast, a framework is more agile, flexible, and versatile and leaves more room to adapt to the problem at stake (Sols, 2016).

3.2 Systems Architecting

3.2.1 Introduction

Systems architecting is the process of defining the systems architecture. ISO/IEC/IEEE 42010 (2011) defines systems architecting as *"a process of conceiving, defining, expressing, documenting, communicating, certifying proper implementation of, maintaining, and improving an architecture throughout a system's life cycle."*

Systems architecting can support exploring the needs and design of a system (Maier & Rechtin, 2009). Crawley et al. (2004) highlighted the importance of systems architecting to enable a way to understand complex systems, design and manage them, and provide long-term rationality of decisions made early in the project. Sillitto (2009) stated that the systems architecture is not an end in its own right, merely a means to enable the creation of successful systems.

3.2.2 Systems Architecting Frameworks

It exists several architectural frameworks to support the development of systems architecture. Architectural frameworks intend to provide a standard approach to architecture (Greefhorst, Koning, & Van Vliet, 2006). Reviews of existing architectural frameworks are presented in (Reichwein & Paredis, 2011) and (Greefhorst et al., 2006). The review given by Greefhorst et al. focused on the differences in the frameworks and concluded that one should adapt the architectural framework to the goal and context.

3.2.3 Architectural Reasoning

Architectural reasoning is the process of developing the systems architecture. Wu (2007) presented a schematic model for architectural reasoning, describing it as a recursive process driven by system requirements, available domain knowledge, and available design knowledge.

Muller (2004) defined a framework to support the architectural reasoning process called CAFCR. The CAFCR framework decomposes the architecture into five views, customer, application, functional, conceptual, and realization. The author suggested different sub-methods to support the systems architecture development within each view. To integrate the views, he used the system qualities. The CAFCR views and qualities are typically on a rather abstract or generic level. To explore the specific, he proposed the use of storytelling. Finally, Muller proposed the thread of reasoning to combine the insights from the abstract and specific and to move between the views.

3.2.4 System-Level Decision-Making

In defining the systems architecture, system-level decisions about the system must be made. Maier (2019) defined architecture as a set of decisions about the system, making systems architecting a decision-making process. Madni (2013) also highlighted the importance of decision making in systems architecting, describing systems architecting as an integrative, decision-rich activity that requires the continuous generation and evaluation of options.

Architectural decisions involve balancing conflicting needs and understanding the main trade-offs and the coupling between decisions (Crawley et al., 2016; Maier & Rechtin, 2009). Moullec, Jankovik, and Eckert (2016) stated that systems architecture decisions are difficult because of fuzziness and lack of information, often combined with conflicting objectives. Conflicting objectives is a returning concern in system-level decision-making (Griendling, Salmon, and Mavris, 2012; Topcu and Mesmer, 2018). An essential aspect of decision-making is balancing the stakeholder's needs. Topcu and Mesmer (2018) stated *that "the essence of systems engineering lies in enabling rational decision-making that is consistent with the preferences of the system's stakeholders."* The challenge of meeting the stakeholders' preferences and needs is even more challenging when considering systems of systems (Griendling et al., 2012; Xu, 2012).

3.3 The Concept Stage of System Development

3.3.1 Introduction

In the concept stage, the main activities include defining the problem space, characterizing the solution space, identifying stakeholder needs, and exploring feasible concepts (INCOSE, 2015). This stage is a critical part of the systems engineering approach, and the decisions taken in this stage are strategic and significantly influence all subsequent phases of system development (Verma, Smith & Fabrycky, 1999). The definition of the systems architecture occurs in the concept stage and is one of the key activities in this phase (Haveman, 2015). As new products are becoming more complex and multi-disciplinary, with shorter development cycles, the role of the systems architecting in the concept stage is becoming more critical (Bonnema, 2011).

The objective of the concept stage is to develop a concept that fulfills the system's objectives. Liu, Blight, and Chakrabarti (2003) stated that the conceptual design process should contain two kinds of steps, divergent in which alternative concepts are generated and convergent in which these are evaluated and selected. Typical approaches for concept generation includes brainstorming, sketching, Morphology analysis, and TRIZ (Kannengiesser et al., 2013). A more extensive list of concept generation techniques is provided by Daly et al. (2012). In the convergent phase, the identified concepts should be evaluated to find the concept that best fits the system's objective. Traditional tools for decision support include design structure matrix and decisions trees (Crawley, Cameron & Selva, 2016, p. 320). However, systems architecture decisions have characteristics and metrics that differentiate them from other types of decisions. The combinations of these characteristics and metrics make traditional decision support tools less suitable (Crawley, Cameron & Selva, 2016, p. 326).

3.3.2 Challenges in Multi-Disciplinary System Development

The challenge of technical silos hindering effective systems engineering is often prevalent in interdisciplinary teams (Delicado, Salado, & Mompó, 2018). McLachlan (2020) claimed that silos are an obstacle to knowledge transfer in the energy industry and manifest in the inability to deliver value. He proposed using systems thinking approaches to break down the silos. Further, he claimed that applying systems thinking can support value creation in the early phases and protect that value through the project lifecycle.

Borches (2010) presented a survey from the context of magnetic resonance imaging (MRI) systems, exploring the barriers faced when evolving complex systems. He found the obstacles to be managing system complexity, lack of system overview, ineffective knowledge sharing, finding system information, and communicating across disciplines and departments. Similar challenges are reported in the Aberdeen Group's research, a survey of 160 enterprises developing mechatronic products (Boucher & Houlihan, 2008). They found the lack of cross-functional knowledge as the top challenge, followed by the challenge of early identification of system-level problems. They stated that problems are often not identified until the physical prototype is developed, highlighting the need for early prediction and models of the system's behavior. Tomiyama et al. (2007) also discussed the lack of collaboration across technical disciplines. They categorized the challenge into three types of difficulties: (i) lack of a common inter-disciplinary language; (ii) the inherent difficulties in dealing with many stakeholders; (iii) multi-disciplinary product development creates inter-disciplinary problems. Finally, they linked the lack of cross-functional expertise to the challenge of anticipating system problems in the early design stage. Heemels and Muller (2006) also highlighted the lack of a common language between engineers as a challenge in decision-making in the industry. Further, they identified problems related to the fact that the design choices are made implicitly, based on experience, intuition, and gut feeling, and highlighted the lack of tools and methods to reason about the time-varying aspects during design.

3.4 Decision-Making

3.4.1 Introduction

Decision-making is widely discussed in the literature and is explored across various domains, including business, health, and education (Hallo et al., 2020). The decision-making process consists of generating alternatives, evaluating them, and choosing the most suitable concept. Hallo et al. (2020) stated that the decision-making process is a cognitive process that can be rational or less rational and driven by explicit knowledge, implicit knowledge, or one's belief systems. Robinson et al. (2017) also emphasized the cognitive process's role and stated that *"decision-making is a multifaceted, socially constructed human activity that is often non-rational and non-linear."*

According to Simmons (2008), decision support is the *"task of assisting decision-makers in making a decision."* He split between programmed decisions, characterized as *"routine, well-defined, can be modeled and optimized precisely and solvable by established procedures,"* and non-programmed decisions, characterized as "*non-routine, weakly-defined, usually significant impact and often solved by heuristics search of general problem-solving methods."* The first group is typical decisions in engineering design, while the second group is typical decisions in systems architecting.

3.4.2 Frameworks for System-Level Architectural Decisions

Bijlsma et al. (2019) gave an overview of quantitative reasoning methodologies to support architectural decisions. They stated that these approaches often focus on software. Of the methods focusing on system-level decision-making, they included BoDerc (Heemels & Muller, 2006), ArchDesigner (Al-Naeem et al., 2005), and Geeglee (Jankovic, Holley & Yannou, 2012). The same article presented a decision support methodology for evolutionary, focusing on embedded systems (Bijlsma et al., 2019). This methodology consists of three elements: a structure to model the systems qualities and realization, a method for reasoning and decision-making, and a formalism to express the structure.

The Boderc design methodology for high-tech systems aims to support efficient evaluation of design choices over multiple disciplines (Heemels & Muller, 2006) They split the method into three high-level steps. The first step is the *preparation of design*, identifying realization aspects of concern, key drivers, and requirements, and making the core domain explicit. The next step is to *select critical design aspects*, which is done by identifying and quantifying tensions and conflicts. The last step is the *evaluation of design aspects,* using models and measurements.

Muller (2014) gave a similar flow from problem to solution, consisting of 4 steps: 1) problem understanding, 2) analysis, 3) decision, and 4) monitoring, verifying, and validating. The first step is to create an understanding of the problem. One needs to explore both the problem and solution space to do this. Next, in the analysis steps, one should explore multiple propositions through systematic analyses. The following step is to decide by reviewing the analysis and documenting and communicating this decision. Finally, the solution should be verified and validated by measurements and testing.

Simmons (2008) presented a computational framework for decision support called Architecture Decision Graphs (ADG) framework. The context for his work was space missions. The framework aims to support human decision-making by representing and transforming the architectural problem into a computational problem to simulate the outcome of a decision. A similar architectural framework for analyzing spatial and temporally distributed resource extraction systems was presented by Aliakbargolkar and Crawley (2012), using the offshore production field as an example.

3.4.3 Decision-Making Methods in an Industrial Setting

Renzi, Leali, and di Angelo (2017) presented a review of the state of art and classification of decision-making methods in industrial design. They identified three main groups of decision-making for solving engineering design problems: Multi-Criteria Decision Making (MCDM), Problem Structuring method, and Decision-making Problem-solving methods. Multi-Criteria Decision Making (MCDM) provides strong decision-making in domains where choosing the best alternative is highly complex (Mardani, Jusoh & Kazimieras, 2015). Broniatowski (2018) stated that engineers rely on techniques to support selecting a subset design within a large trade space, and techniques like Pugh Matrix (Pugh, 1990) and Analytical Hierarchy Process (AHP) (Saaty, 1994) are commonly used. Although such methods are widely used in industrial applications, they have several shortcomings. For example, Xu (2012) stated that such methods lack focus on the decision's uncertainty, stating the outcomes from analyses based on such models appear to be free of uncertainties, which could be misleading to the inexperienced.

3.5 Conceptual Modeling

3.5.1 Introduction

Modeling is a central activity in systems engineering to understand and simplify reality through abstraction. Ramos, Ferreira, and Barceló (2012) stated that *"from brain representations to computer simulations, the models are pervasive in the modern world, being the foundation of systems' development and systems' operation."* A conceptual model is an abstract, simplified representation of a system of interest (Harrison & Waite, 2012). Fujimoto and Loper (2017) stated that as all models are a simplification of the real world, all modeling involves conceptual modeling.

Lavi, Dori, and Dori (2020) stated that in model-based systems engineering, a conceptual model is the product of the system representation process. Further, they stated that conceptual modeling facilitates the system design process by allowing for a shared representation of system architecture, helping to manage complex knowledge and resolve conflicts and ambiguities. Dori (2003) emphasized the role of the human in the modeling, stating that *"models show certain aspects of that reality, including function, structure, and dynamics, as perceived or envisioned by the human modeler or system developer.*"

An important field of application for conceptual models is the field of simulations. A commonly used definition of conceptual models is given by Robinson (2008), stating that *"the conceptual model is a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions, and simplifications of the model."* However, it is not a widely accepted definition or understanding of the conceptual model within the field of simulation (Robinson, 2020). In Robinson et al. (2015), five leading researchers within the field discussed their views and beliefs on conceptual modeling and highlighted the lack of common ground. Hoppenbrouwers, Proper, and van der Weide (2005) contributed to the definition of conceptual modeling, focusing on the process of creating the models. They stated that the goal of modeling is to reach a state where all participants have some degree of shared understanding. Therefore, there is a need to facilitate communication and knowledge sharing between domain experts and modelers to enable this.

The conceptual model is a central part of Checkland's Soft Systems Methodology (SSM) (Checkland, 1999). The SSM splits between the *'real world'* and *'systems thinking'* activities. The systems thinking activities contain the 'root definition' and 'conceptual model.' The root definition is a concise construct of a human activity system, stating what the system is. Based on the root definition, the conceptual models elaborate on what the system does. In this methodology, the conceptual models are used to make a structured investigation of a *'real-world problem.'* Checkland and Tsouvalis (1997) emphasized that the conceptual model should be *"seen as 'hows' rather than 'whats'.."* and that *"building conceptual models is a matter of experience and skill."* Another conceptual model from system thinking is Boardman's systemigram (Boardman & Sauser, 2008). Systemigrams are used for understanding and identifying significant elements of the system of interest, representing the interrelationships and diverse expression of stakeholder concerns and needs (Cloutier et al., 2015). McDermott (2019) stated that conceptual models could capture higher-level textual or descriptive models of the problem that can then be decomposed into lower sets of measures that can be assessed analytically. He highlighted the importance of the human's ability to move between analytical and conceptual models. At the same time, he introduced the challenge of visualization to get the appropriate linkage between high-level conceptual representations and low-level analytics.

Our research builds on the work of Muller (2004), who defined conceptual models as "*models that are sufficiently simplified to help architects to understand, reason, communicate and make decisions*" (Muller, 2015b). Further, he defined conceptual models as a hybrid of empirical and first principle models (Muller, 2021). Empirical models describe what we observe and measure, while first principle models explain the behavior of a property, using first principles from science, such as laws of physics. Finally, he emphasized the need for the conceptual models to be *"simple enough to understand and reason, while it must be realistic enough to make sense."*

3.6 Systems Engineering Application in the Energy Domain

3.6.1 Introduction

The focus on system engineering in the energy industry is growing, and the establishment of the INCOSE Oil and Gas working group in 2016 is proof of this. The Norwegian subsea industry is increasingly applying systems engineering processes to ensure their projects' success (Mjånes, Haskins & Piciaccia, 2012). Wee and Muller (2016) stated that the supplier company typically uses a project execution model built on the Vee model. An example of the application of the system engineering process to subsea development is given by Yasseri (2014).

3.6.2 Decision-Making and Concept Evaluation in Early-Phase of Energy Domain

Decision analysis is vital in the early phase of field development to optimize the production profile and improve project performance (Santos, Gaspar & Schiozer, 2018). The literature on concept evaluation in the early phase of field development shows extensive use of detailed simulations to support decision-making. An example is given by Angert, Isebor, and Latvak (2011), who used a company-developed operation evaluation technology to run a large number of simulations to optimize the field layout. Bratvold and Begg (2008) reviewed the common decision-making practice in the oil and gas industry. They stated that the industry traditionally follows the philosophy that "*given sufficient computing power, we can build a detailed enough model of the decision problem to enable us to calculate the right answer."* They contend that the industry has focused on the downside of uncertainty and not considered the opportunity of creating value by capturing the potential upside. Further, they proposed a decision-making process based on a holistic, dynamic approach, combining Monte Carlo simulation with elements from modeling of systems dynamics. Valbuena (2013) also highlighted the need to exploit the potential upside of the uncertainty. He emphasized the importance of a decision-making process that "*systematically and consistently addresses the different key drivers that affect the outcome in terms of upside and downside risk.*" He proposed a decision-making process performing trade-offs based on the value proposition and the risk to select the best value-risk operation.

Decision-making in the energy industry is often focused on the investment cost, focusing less on the total cost of ownership. Allaverdi, Herberg, and Lindemann (2014) concentrated on the lack of focus on the usage context during the early phase, stating that this, combined with a highly regulated environment, leads to a more risk-averse industry that *"endorses system designs that primarily fulfill their initial requirements with limited anticipation and embedment of properties into the system that have long-term value."* Further, Allaverdi and Browing (2020) proposed a Flexible Design Opportunities (FDO) methodology to systematically and comprehensively account for uncertainty in the early stage of the design process.

Åslie and Falk (2021) stated that the concept selection for a subsea field development requires the decision-makers to do a trade-off, and the multi-criteria evaluation is essential. Their work reviewed the current state of decision-making in the early phase of subsea field development and found Multi-Criteria Decision Making (MCDM) methods to be the dominating methods for supporting concept evaluation. The MCDM serves as an initial concept screening at the system level and is supported by detailed simulation of areas such as flow assurance and electrical analysis (Engen & Falk, 2018). Examples of MCDM methods applied in the early phase of subsea field development are given in (Rodriguez-Sanchez, Godoy-Alcantar, & Ramirez-Antonio, 2012; Lønmo & Muller, 2014; Yasseri, 2014). Solli and Muller (2016) proposed combining the Pugh Matrix with an illustrative Concept of Operations (ConOps) to improve the focus on the operational context during the early phase of concept selection. They found this approach to support stakeholder communication in the early phase and serve as a trigger for discovering opportunities and constraints not initially considered.

3.6.3 Conceptual Modeling in the Energy Domain

There are several examples of the usage of conceptual models to support system design in the energy domain in recent years. Muller, Wee, and Moberg (2015) used physical and dynamic behavior models to show the contributions to the system qualities cost and operation time for a workover system. They found the models to support the communication system understanding with diverse stakeholders. Haugland and Engen (2021) used similar visualizations to support concept evaluation for the subsea connection system and found the visualizations efficient for rapidly sharing key aspects of the system. Solli and Muller (2016) used abstract workflows as a part of their illustrative ConOps in the early phase and found that this can increase the understanding of the operational environment and support a joint holistic picture in multi-disciplinary teams. Finally, Henanger, Muller, and Piciaccia (2016) and Bryn and Muller (2017) studied conceptual modeling to improve the understanding of system tolerances. They concluded that conceptual modeling and budgeting enhanced the understanding and supported discussions across the subsystems.

A tool that has shown promise in improving the system offering in the subsea industry is A3 Architectural Overviews (A3AO) (Muller & Falk, 2018). Several case studies from the subsea industry have explored the use of A3 Architectural Overviews (A3AO) in the early phase (Muller, Wee & Moberg, 2015; Frøvold, Muller & Pennotti, 2017; Løndal & Falk, 2018; Boge & Falk, 2019). A3AO is a tool developed by Borches to communicate architectural knowledge across disciplines and stakeholders in multi-disciplinary projects (Borches, 2010). One of the strengths of A3AO is the use of visual models to represent systems information, as it communicates to a diverse group of stakeholders. Visual workflows are especially useful when communicating with engineers from the physical domain, such as mechanical engineers (Muller & Falk, 2018). In Muller, Wee, and Moberg (2015), the authors showed the A3AO combined with conceptual modeling for a workover system. They found that the A3AO connects the technical system to the business interest and facilitates the stakeholders' discussions. Løndal and Falk (2018) gave another example of the implementation of A3AO. The authors concluded that A3AO is a well-suited tool to improve communication and collaboration within the industry. At the same time, they identified challenges related to implementing this in the industry. They found part of the organization reluctant to implement and use A3AO, mainly due to the time spent making the reports and the lack of integration with existing company tools. Their findings are coherent with the findings of Muller (2015a), who stated that the subsea industry often meets the introduction of more formal methods with skepticism and that they perceive the methods as time-consuming and not applicable.

4 Research Approach

This chapter describes the research approach for the thesis and the rationale for choosing this approach. In the thesis, we have structured the research following Design Research Methodology (DRM) by Blessing and Chakrabarti (2009). We have performed our research in the industrial setting, and in the industry cases, we have applied action research (Checkland & Holwell, 1998) and Industry-as-laboratory (Potts, 1993).

The chapter presents the research design, method, and data collection and processing. Then, we frame the research philosophy applied in the thesis and our approach to theory development. Finally, we present the research ethics and approach to validation of the research.

4.1 Research Design

We have structured the research design following the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009). Figure 8 illustrates the stages in research design, with its associated means and outcomes. The solid boxes show the means, stages, and outcomes described in the framework (Blessing & Chakrabarti, 2009, p. 15), while the dashed boxes indicate the means and outcomes specific to our research.

Our research design consists of four stages, Research Clarification, Descriptive Study I, Prescriptive Study, and Descriptive Study II (Blessing & Chakrabarti, 2009, p. 14). The following describes the research we conducted in each stage.

The ***Research Clarification*** phase focuses on understanding the current situation and the desired situation. The outcome of this phase is the definition of the research goals and objectives. In the research clarification phase, we did an exploratory literature review to understand the current body of knowledge. In addition, we did exploratory studies in the company of research and in the industry to explore current work practice and identify the need for support. Finally, based on the findings from the research clarification, we defined the research questions for the remaining of the research.

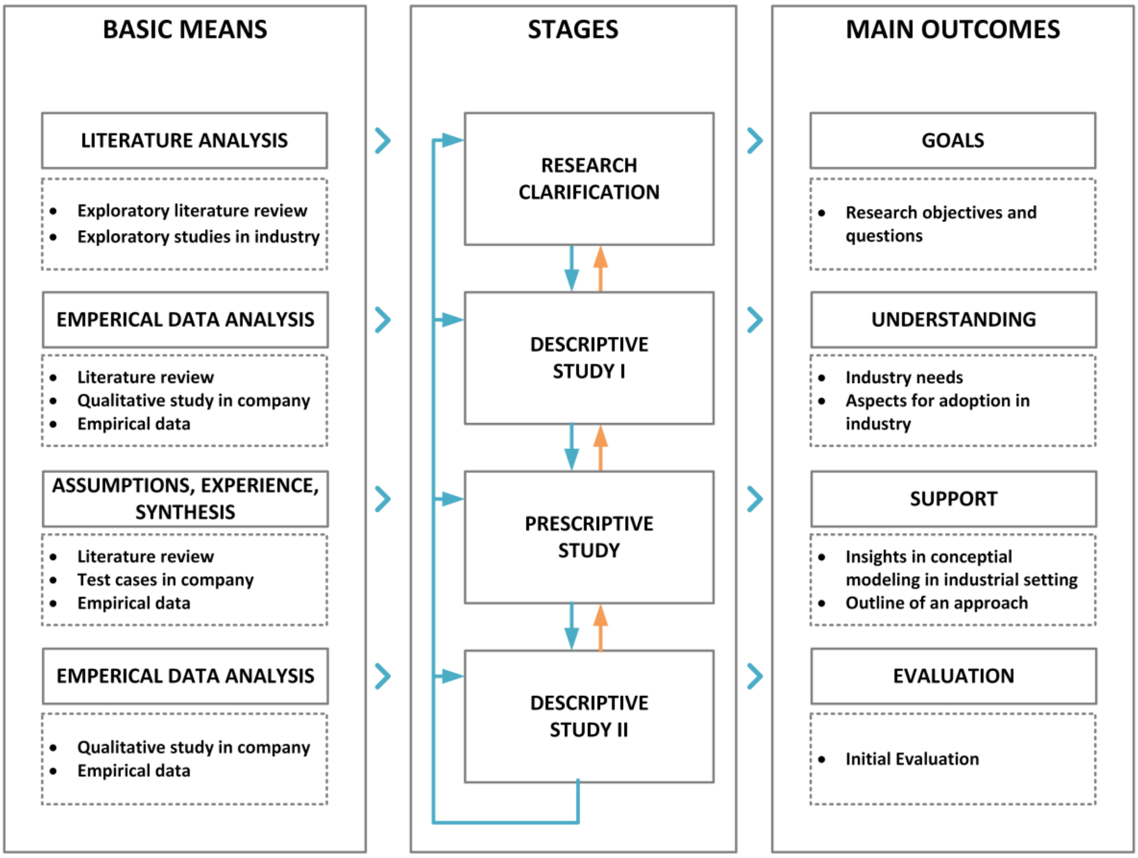

Figure 8: Research design applied in the thesis, adapted from (Blessing & Chakrabarti, 2009, p. 15)

The purpose of the ***Descriptive Study I*** is to elaborate on the current situation. According to the Design Research Methodology, this phase consists of analyzing empirical data to generate understanding. In this phase, we reviewed additional literature related to the current state of decision-making and concept evaluation in the industry. In addition, we did an in-depth study in the company to understand the challenges and needs in their current work practice. From the literature review and the study, we identified a set of aspects that we need to consider when proposing approaches to the industry.

Next follows the ***Prescriptive Study*****.** In this phase, the researcher should use assumptions, experience, and synthesis to develop support. In the prescriptive study, we performed several test cases in the company. Further, we performed a literature review on decision-making and conceptual modeling. The outcome of the prescriptive study was learning and insights into using conceptual modeling in an industrial setting. Finally, based on the learnings from the test cases, we proposed an approach using conceptual models to support system-level decision-making.

The final phase is the ***Descriptive Study II,*** in which the researcher evaluates the support developed in the previous stage. To perform the evaluation, we performed a qualitative study in the company. The research reports an initial descriptive study II. The results from this study are only indicative of the approach's usefulness and indicate the issues and factors that need further evaluation (Blessing & Chakrabarti, 2009, p. 195).

Table 2 shows the research aim and question for each stage and the corresponding appended and supporting articles reporting the findings from each stage.

Table 3: Overview of the articles related to each research stage

Research Stage	Research aim	Appended Articles	Supporting Articles
Research clarification	Explorative studies to clarify research goals and identify the research questions	Article 1 Article 2	Article 6 Article 7
Descriptive study I	RQ1: What are the challenges and needs for improving systems awareness in the early phase of system development in the subsea industry?	Article 3	
Prescriptive study	RQ2: What are the challenges and needs for improving systems awareness in the early phase of system development in the subsea industry?	Article 4 Article 5	Article 8
Descriptive study II	RQ3: How applicable is an approach for conceptual modeling for the early phase of system development in the subsea industry?	Article 5	

4.2 Research method

We have based our research on action research (Checkland & Holwell, 1998) and industry-as-laboratory (Potts, 1993). Table 4 shows the research method applied in each of the articles.

Table 4: Overview of the research methods applied in the articles

Article	Research method applied
Article 1	Industry-as-laboratory
Article 2	Industry-as-laboratory
Article 3	Action research, industry-as-laboratory
Article 4	Industry-as-laboratory
Article 5	Action research, industry-as-laboratory

Lewin first coined action research in the 1940ies to describe work that did not separate the research from the action needed to solve the problem (Lewin, 1947; Torres-Rojas et al., 2015). Avison et al. (1999) describe action research as a research method that solves immediate practical problems while expanding scientific knowledge. Further, they emphasize the strength of qualitative approaches such as action research in explaining what is going on in an organization. Eden and Ackermann (2018) state that action research is an obvious choice when the research objective is to explore theory in relation to practice.

We chose to apply industry-as-laboratory in our research to make the research relevant to the industry. Industry-as-laboratory is a variant of action research in which the researcher actively interacts with the practitioners in the industry. Borches (2010, p. 6) stated that this interaction differs industry-as-laboratory from other case study research, in which the research method depends just on observations, interviews, documents, and the researcher's impression. Potts initially proposed industry-as-laboratory after observing that the *"research-then-transfer"* paradigm failed to influence industrial practice (1993). Still, 30 years later, the gap between research and academia is present. Reich (2019) states, *"In general, however, there are only a small fraction of research results in a design that are adopted by industry. The mismatch between practice and research also goes in the opposite way. There are tools that are used in industry, that might be criticized by some researchers and debated with their proponents"*.

Using the industry-as-laboratory as a research method allows us to collect data about the industry's current work practice and influence the work practice. The research method is beneficial for our research to understand the industry in-depth. However, conducting action research carries risks of researcher bias and threats to the validity of the results. Section 4.5 further describes measures taken to reduce this risk and evaluate the validity of the results.

4.3 Data Collection and Processing

The research has collected qualitative data through surveys, interviews, technical documentation reviews, active participation, and observations. Table 5 shows the data collection for each of the articles.

Table 5. Overview of the data collection methods applied in the articles

Article	Data collection
Article 1	Review of technical documents Informal interviews
Article 2	Observation and active participation Survey
Article 3	Semi-structured interviews Survey Review of technical documents Observations and active participation
Article 4	Informal interviews Review of technical documents Observation and active participation
Article 5	Synthesis of 4 years of research and observation Survey

The research has collected a vast amount of data through interaction with practitioners in the industry. Throughout the research, the candidate has been co-located in the company of research, taking part in the daily work. Table 6 shows an overview of the candidate's location during the research.

Table 6: Overview of the candidate's location in the industry during the research

Period	Location	Description
January 2018 – June 2019	System Development Project	During this period, the candidate took part in a system development project. The system development project was a project that started in the company in 2018 and aimed to evolve the next-generation subsea system for the Norwegian continental shelf. The team consisted of 14 engineers co-located in an open office space. The candidate was an active part of the project, acting as a system engineer.
June 2019 – March 2020	Concept Study Department	The candidate sat in an office area together with the systems engineers working on concept studies during this period. While sitting in the area, the candidate passively and actively observed study meetings and took part in the department's daily discussions.
March 2020 – September 2021	Home office	Due to the global Covid-19 pandemic, the candidate and the other company resources were located in the home office from March 2020. During this period, the author regularly interacted with systems engineers working with concept studies and project execution through Teams meetings. In addition, she attended technical meetings on ongoing studies.

Figure 9 illustrates the data we collected for each article and when and where we collected them. The following sections describe the data collection and processing in more detail.

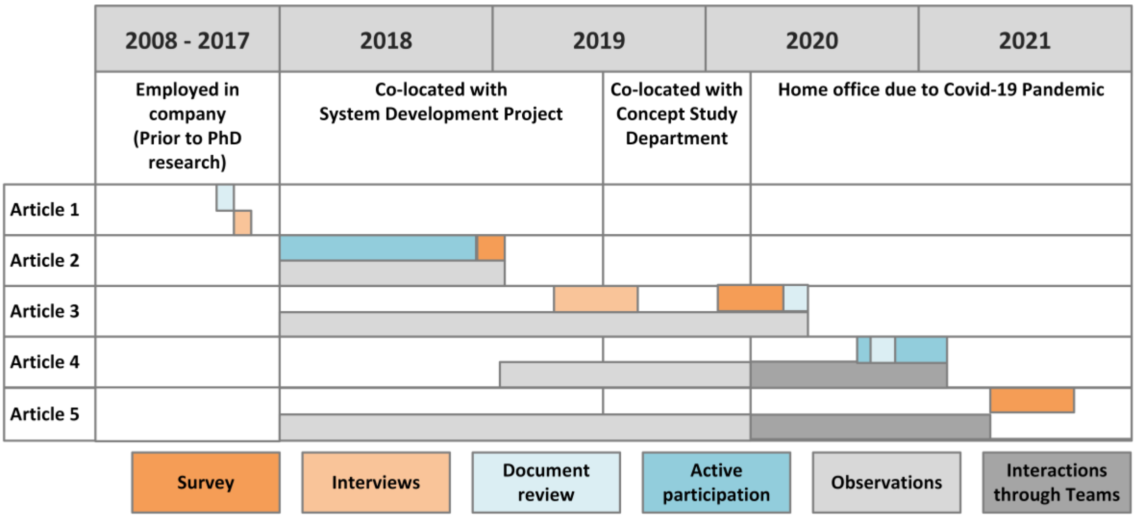

Figure 9: Timeline for data collection

4.3.1 Interviews

In articles 1, 3, and 4, we collected data through interviews. Table 7 shows the number of and types of resources we interviewed for each article.

Table 7: Participants in the interviews

Article	Type of resources	No. of interviewees
Article 1	Managers from systems engineering groups	3
Article 3	Systems engineers working in concept studies and project execution	7
Article 4	Systems engineers working in concept studies	2

In Articles 1 and 4, we conducted informal interviews, and we conducted the interviews as meetings with the resources. The interviews had a predefined topic but without any guide for questions. During the interviews, we took written notes.

In article 3, we conducted semi-structured interviews. We used a prepared set of open-ended questions to guide the interviews while allowing departures and the exploration of other topics. We recorded these interviews. The recording from the seven interviews was in a total of 3 hours and 17 minutes. We transcribed and analyzed all interviews. As the interview was explorative, the transcripts were not suited for formal coding. Instead, we used the transcripts to identify reoccurring topics.

4.3.2 Survey

In articles 2, 3, and 5, we collected data through surveys. Table 8 shows the type of resources we invited to the surveys and the number of responses for each survey.

Table 8: Participants in the surveys

Article	Type of resources	No. of responses
Article 1	Project team in system development project	14
Article 3	Systems engineers and sub-systems engineers	126
Article 5	Systems engineers	37

The majority of the surveys asked the respondent to evaluate statements using a five-point Likert scale (Likert, 1932). The five-point Likert scale was chosen due to recognizability, as this is the scale commonly used in the company and research in the domain. For all statements, the survey gave the participants the possibility to answer "I do not know" or "Not applicable" to allow them to skip questions when they did not have the experience or knowledge to respond. Further, we applied a forced-response function in the questionnaires, meaning that the respondent needed to evaluate each statement in each section before proceeding with the survey. The forced-response function ensures that the survey did not record any missing values in the data set.

To analyze the statements, we evaluated the distribution of responses and the Net Promoter Score (NPS) (Muller, 2013; Reichheld, 2003). When calculating the Net Promoter Score, we are considering "Strongly Agree" as a promoter, "Agree" as neutral, "Neither Agree nor disagree," "Disagree," and "Strongly Agree" as detractors. This assessment is strict, as only "Strongly Agree" is regarded as a promoter. However, we consider this a valid assessment for the type of statements we gave in the surveys. For example, in article 5, the statements ask regarding the approach supportiveness. In this case, "Agree" is an expected result and is considered neutral. Consequently, "Strongly Agree" would be better than expected and is a promoter. Likewise, a score below "Agree" would be less than expected, and therefore we regard those as detractors.

The surveys for articles 3 and 5 also included open-ended questions to allow respondents to elaborate on their responses. We used manual coding to analyze the responses given in the open-ended questions.

4.3.3 Review of Technical Documents

Throughout the research, we have actively used the technical documentation available in the company as a source of information on the technical system and the work practice. In articles 1, 3, and 4, we reviewed technical documentation specifically for the article. Table 9 shows the type and quantity of documents reviewed in the articles.

Table 9: Technical documents reviewed

Article	Type of documents	No. of documents
Article 1	Technical reports	30
Article 3	Study reports, PowerPoint presentations, and drawings	14
Article 4	PowerPoint presentations, System drawings, Excel sheets	8

4.3.4 Active Participation and Observations

In the research, we have collected data from active participation and observations in the industry. Table 6 summarizes the overview of the researcher's location in the industry during the duration of this thesis. The candidate interacted with the engineering teams in technical discussions and participated in workshops and meetings in her daily work. In addition, we applied methods and tools to industrial problems. We collected the observation and insights gained from the interactions in a research logbook.

4.4 Research Philosophy and Approach to Theory Development

Saunders, Lewis, and Thornhills (2019) proposed the research onion, identifying the layers to consider for defining the research approach. Figure 10 shows an adaption of the research onion. The grey circles indicate where we position our research. The inner layers, shown as orange in the figure, describe the research method and data collection strategy, as described in the previous sections. The outer layers, shown in blue, are related to the research philosophy and approach to theory development. This section further describes the outer layers.

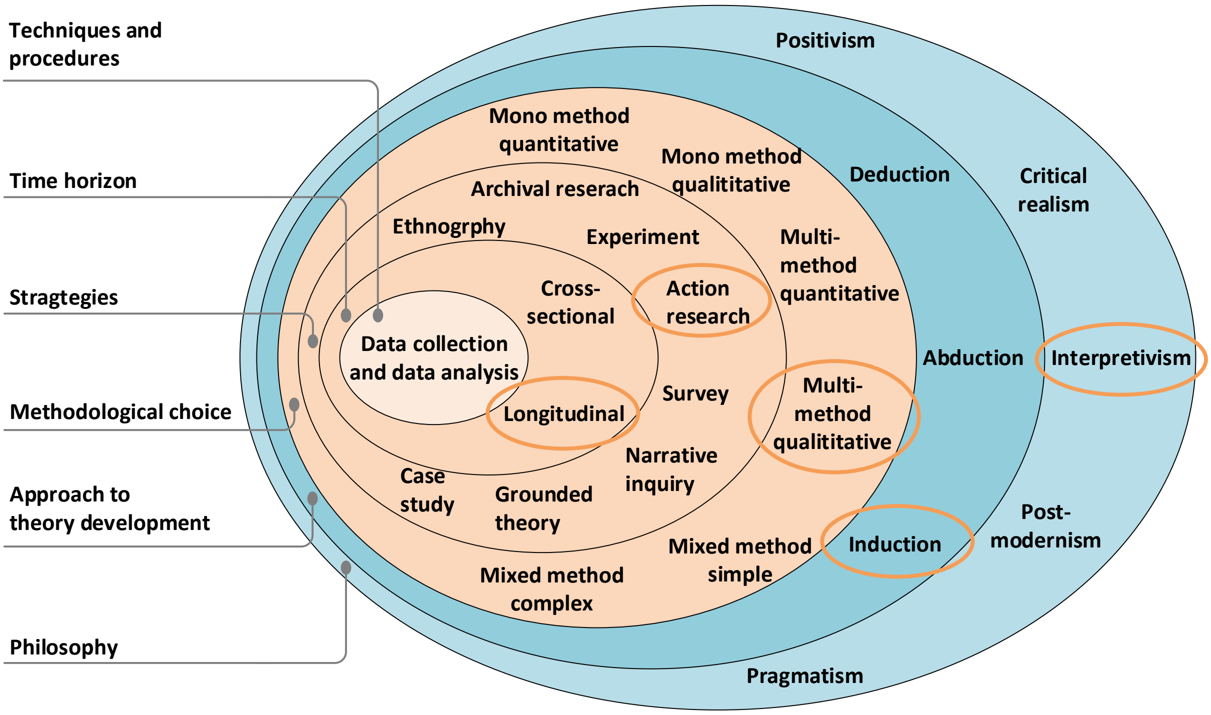

Figure 10: Research onion, adapted from (Saunders et al., 2019, p. 130)

The second outmost layer describes the approach to theory development. The relation between data collection and analysis and between theory and data can be discussed in terms of deduction, induction, and abduction (Kennedy & Thornberg, 2017, p. 50). The outmost layer is the research philosophy. Research philosophy refers to a system of beliefs and assumptions about developing knowledge (Saunders, Lewis, and Thronhill, 2019, p. 130). They defined five major research philosophies, positivism, critical realism, interpretivism, post-modernism, and pragmatism. The research approach followed in this research leans towards an interpretivism philosophy. Interpretivism is based on the assumption that reality is complex and socially constructed through culture and language. Interpretivism is commonly used in action research, as it captures and communicates the reality of a particular environment as interpreted by the researchers at a point in time (Siau & Rossi, 2011).

As described in Section 4.1, we used the research clarification phase to understand the company's current practice and identify the needs for improvement. This approach relates closely to the interpretivism philosophy. An important aspect of the interpretivism philosophy is that rather than developing and testing a hypothesis, it investigates research questions focused on understanding phenomena in natural settings (de Villiers, 2005). Interpretivism lends mainly to qualitative data collection. Our research has collected diverse qualitative data to understand and investigate the problem in its context.

Reichertz (2013, p. 131) summarized the difference as *“abduction searches for theories, deduction for predictions, induction for facts.”* Sale and Thielke (2018) stated that qualitative research generates meaning through a systematic approach to induction and deduction and thus is essential to the scientific method in the pursuit of knowledge. Most research applies a combination of the different approaches of reasoning to generate knowledge. Our research uses observation and data from the industrial setting to search for facts and test theories. Hence, we position our research mainly in induction, but we have also applied abduction.

4.5 Approach to Validation of Research Results

To evaluate the validity of the research results, we consider their trustworthiness. Guba (1981) proposed four major aspects of trustworthiness: *truth value, applicability, consistency,* and *neutrality.* Further, he defined the associated terms for each aspect of scientific and naturalistic research, as presented in Table 10.

Table 10: Scientific and Naturalistic Terms for the four aspects of trustworthiness, adapted from (Guba, 1981)

Aspects	Scientific Term	Naturalistic Term
Truth Value¨	Internal validity	Credibility
Applicability	External validity / Generalizability	Transferability
Consistency	Reliability	Dependability
Neutrality	Objectivity	Confirmability

Our research is qualitative and positioned within interpretivism, which implies we should use naturalistic terms for evaluation. Korstjens and Moser (2018) state that in addition to these four criteria, one should also consider *reflexivity*. Consequently, we use five criteria to evaluate the trustworthiness of our research: credibility, transferability, dependability, confirmability, and reflexivity. Table 11 present the definition of the five criteria.

Table 11: Definition of criteria for evaluating trustworthiness, adapted from (Korstjens & Moser, 2018)

Criteria	Definition
Credibility	The confidence that can be placed in the truth of the research findings. Credibility establishes whether the research findings represent plausible information drawn from the participants' original data and is a correct interpretation of the participants' original views.
Transferability	The degree to which the results of qualitative research can be transferred to other contexts or settings with other respondents. The researcher facilitates the transferability judgment by a potential user through thick description
Dependability	The stability of findings over time. Dependability involves participants' evaluation of the findings, interpretation, and recommendations of the study such that all are supported by the data as received from participants of the study.
Confirmability	The degree to which the findings of the research study could be confirmed by other

	researchers. Confirmability is concerned with establishing that data and interpretations of the findings are not figments of the inquirer's imagination but clearly derived from the data.
Reflexivity	The process of critical self-reflection about oneself as a researcher (own biases, preferences, preconceptions), and the research relationship (relationship to the respondent and how the relationship affects the participant's answers to questions).

To evaluate the criteria credibility, we have employed the eight-point checklist proposed by Maxwell (2012, pp. 126–129), which includes;

1) *Intensive, long-term involvement.* Long-term involvement allows for repeated interviews and data collection and will provide more complete data on specific situations and events than any other method.
2) *"Rich data."* Rich data refers to collecting detailed and varied data to provide a complete picture of what is going on.
3) *Respondent validation.* Systematically seeking feedback about the collected data and conclusions from the research objects to rule out misinterpretations.
4) *Intervention.* Intervention refers to the researcher's presence and impacts on the research objects and research context.
5) *Searching for discrepant evidence and negative cases.* Identifying and analyzing discrepant data and negative cases to avoid ignoring data that do not fit a theory.
6) *Triangulation*. Collecting data from a diverse range of people and contexts using various methods reduces the chance of systematic biases.
7) *Numbers.* Using numbers to quantify qualitative data, to test and support claims.
8) *Comparison.* Comparing the research setting to other settings to validate the findings.

In addition to evaluating the research's trustworthiness, we specifically evaluate the research by considering *researcher bias* and *reactivity.* These two aspects are the main threats to validity in qualitative research (Maxwell, 2012, p. 124). Researcher bias refers to the researcher's subjectivity influencing the selection and analysis of the data. Reactivity refers to the effect of the researcher on the setting or individuals studied. In qualitative research, the aim is not to eliminate these threats but rather to acknowledge potential bias and reactivity and explain how to deal with them. Norris (2007) states that bias in research stems from various sources and that it is not possible to construct rules for judging studies or specify procedures that eliminate bias error. Further, he states that an honest reflection of the role of bias is needed to enhance the quality of the research.

In the appended articles, we have discussed the specific threats of validation related to the data collection reported in the article. Finally, chapter 7 discusses the overall validity of the research using the approach described in this section.

4.6 Research Ethics

The thesis followed Norwegian National Research Ethics Committee's guidelines for ethical research[1]. We obtained approval from the Norwegian Centre of Research Data (NSD) research (reference 154199). The research has collected data through interviews and surveys. We have treated all data according to the Personal Data Act[2], following the guidelines given by NSD[3]. We have anonymized all collected data in the thesis according to the requirement from NSD.

[1] https://www.forskningsetikk.no/en/guidelines/

[2] https://lovdata.no/dokument/NL/lov/2018-06-15-38/

[3] https://www.nsd.no/personverntjenester/

When recording the interviews, we informed the participant about the recording, the nature of the research, and their rights. Appendix 1 presents the information document. All participants signed consent before the interviews. The recording and transcripts did not contain any personal information.

In the research, we conducted several surveys. In all surveys, the participant was given information about the nature of the research before taking part. Appendix 1 presents the information documents used for each survey. To ensure the safe treatment of personal data, we administrated the surveys through the tool nettskjema.no, a survey solution developed and hosted by the University of Oslo[4]. The personal data collected in the survey includes e-mail addresses. At the start of the survey, we asked for participants' consent. In the data collected, we replaced the e-mail with a numeric key and kept the relationship between the numeric key and the e-mails in a separate file to protect personal information. We deleted this file after completing the research. We have treated all data in this thesis as strictly confidential. The data were used only for the purpose they were collected and have only been available to the researchers.

We have conducted our research in close collaboration with the industry. Still, the company of research has not had the possibility to influence the data collection or the research results or in any way influence the integrity of the research. To avoid confidentiality issues, the company reviewed all articles before publishing.

[4] https://nettskjema.no/

5 Summary of Appended Articles

5.1 Introduction

This chapter presents a summary of the articles appended to this thesis. Figure 11 shows an overview of the articles and their relation to the research design described in Section 4.1.

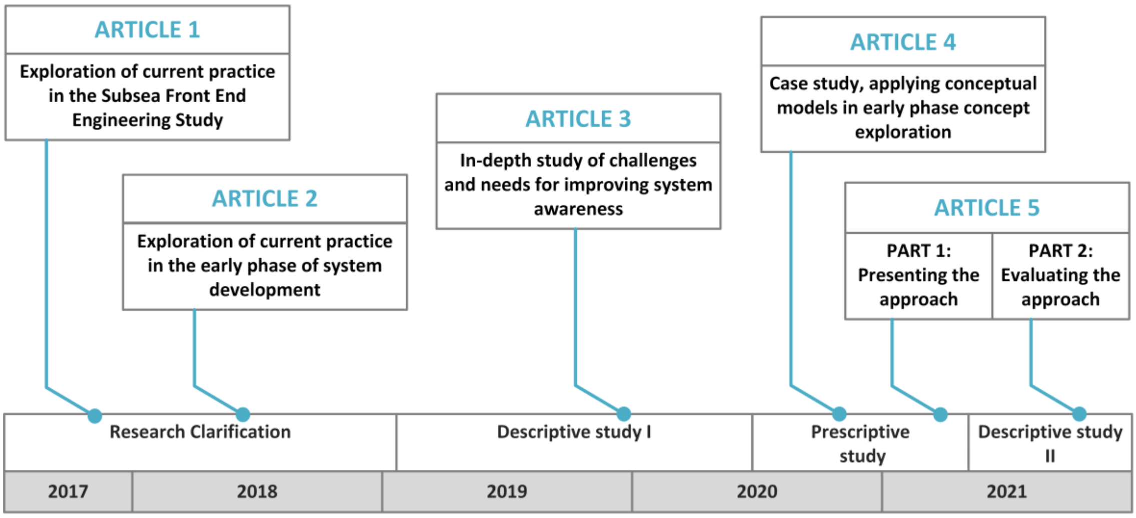

Figure 11: Overview of the appended articles presented in this section

Articles 1 and 2 are both parts of the research clarification phase. These two articles explore the current practice in the early phase of system development. The results from these two articles supported the definition of the research goals.

Article 3 is a part of the descriptive study I. The article presents an in-depth study to further explore the industry's challenges and understand the need for improving systems awareness. Further, we use the study and literature to define important aspects to consider to achieve adaptation of approaches in the industry.

Article 4 presents a case study applying conceptual models to support reasoning in the early phase concept evaluation. In Article 5, we synthesize the insights from this case study and our interactions with practitioners throughout the research and propose an approach to using conceptual modeling to support system-level decision-making. Article 4 and the first part of Article 5 are both parts of the prescriptive study. The second part of Article 5 is in descriptive study II, presenting an evaluation of the proposed approach.

The following presents a summary of the results from the appended articles.

5.2 Article 1

Title: Application of a System Engineering Framework to the Subsea Front-End Engineering study

In this article, we studied the current engineering practice in the subsea front-end engineering study in the company of research. The article applies industry-as-laboratory (Potts, 1993). We collected data from technical documentation and interviews. In addition, the article presents a literature review on systems engineering and model-based systems engineering, focusing on application in the subsea industry.

To understand the current engineering practice, we reviewed 30 reports from front-end engineering studies performed between 2013 and 2017. The study showed that the client was the only stakeholder considered in most cases. Consequently, the studies only considered the client's needs, neglecting the needs of other actors such as the vessel operators, interfacing systems, and topside facility. Another important finding from the study of the reports was that even if the front-end engineering studies are known as concept studies, in most cases, the client does not ask for a concept evaluation but rather dictates a given solution.

At the time of the study, the subsea industry was changing. To understand the impact of the changes to the front-end engineering studies, we conducted informal interviews with three key resources from the company. From the conservations, we find three significant changes that affect the studies. Firstly, there was a trend in the market that the client no longer dictated the solution but rather increasingly was asking the company to develop concepts. Secondly, the contract structure in the industry was changing, and more contract was covering both SPS and SURF scope, demanding a greater focus on the operational context. Finally, the market situation sets demand for a shorter period from study to execution, demanding effective engineering processes.

To analyze the company’s current process for systems engineering in the early phase, we compared the company processes to Sols' Systems Engineering Framework (Sols, 2014). We proposed a new process to mitigate the challenges found in the document study and the interviews. Figure 12 shows the proposed process, where darker blue indicates steps in the existing process, and the lighter blue indicates new steps.

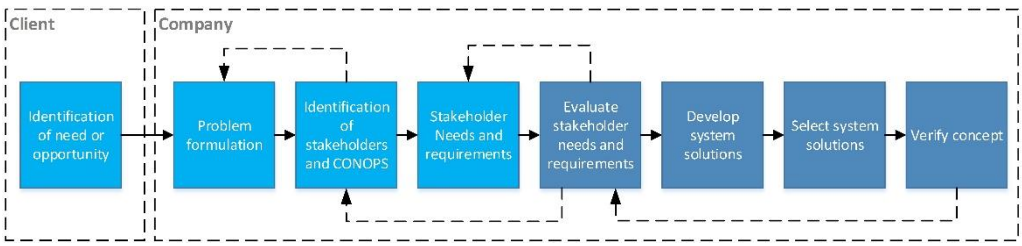

Figure 12: Proposed systems engineering process for field development studies (Article 1 © 2018 INCOSE)

The article also presented a case applying the proposed process to a field development study to illustrate the use. The case shows how unformal models and simplified cost models could support concept development and evaluation. Figure 13 shows an example of the visualizations presented in the case. In the example, we use a visual representation of the workflow to identify the stakeholders throughout the system life cycle.

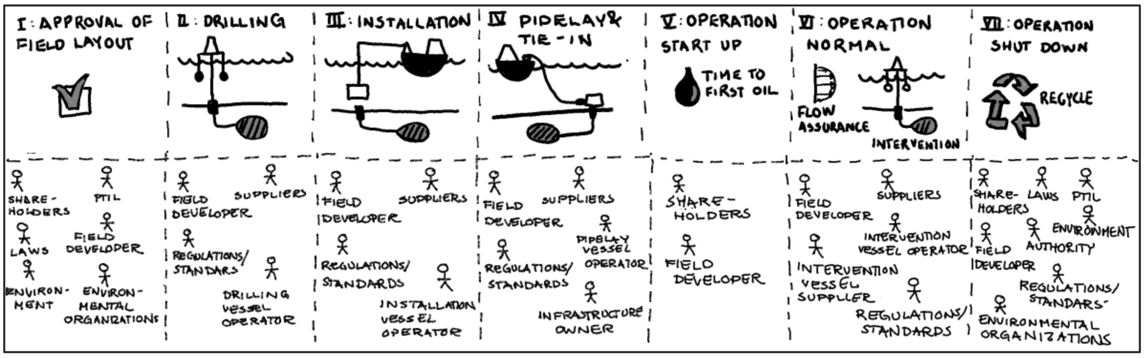

Figure 13: Example of unformal models from the case study (Article 1 © 2018 INCOSE)

The article finds that the visual models communicate well with different stakeholders. Furthermore, visual models reduce the risk of misinterpretations compared to textual documentation. Finally, the article finds that using such models is suitable for introducing the concept of modeling in the early phase and setting the company up for more formal modeling in later project phases.

5.3 Article 2

Title: Architectural reasoning in the conceptual phase - a case study in the oil and gas industry

This article presented a literature review of architectural reasoning and its role in the concept phase. In addition, the article presents an industry case evaluating the work process and tools used in a system development project. In the research, we used industry-as-laboratory (Potts, 1993), and for one year, we actively participated in the project team. We gathered the data in the industry case from observations of daily work and a survey.

In the industry case study, we followed an engineering team working on a system development project in the company of research. The project we followed aimed to develop the next-generation configurable subsea system, focusing on reducing weight and installation costs. The team consisted of 14 engineers from different engineering disciplines, co-located in an open office area.

The development project started with a high-level business requirement from their management. In the initial phase, the engineers defined the problem to solve. To do this, they explored the design and domain knowledge in the company to understand the tension and issue of the existing systems. Further, they explored the prospect in the market to understand the customers' needs for a new system. Based on the knowledge gathered in the problem understanding, the team selected the system issues they should prioritize to further explore in the project. Finally, the team proceeded with evaluating design options for these issues. Figure 14 summarizes the workflow the project team used.

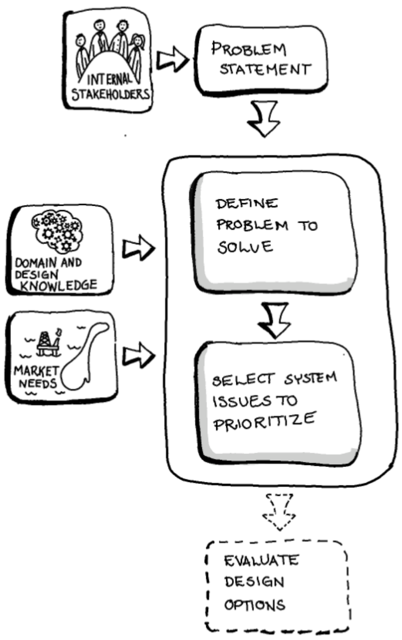

Figure 14: Workflow used in industry for problem exploration (Article 2 © 2019 IEEE)

The article also evaluated the tools and techniques the team applied in their problem exploration. The project team followed a lean engineering work process (Ward & Sobek

II, 2014), and consequently, they used the *A3 Problem-solving tool* (Shook, 2008). In addition, the team had *workshops identifying tensions and issues* with the current system and *lesson learned workshops*, sharing experiences from previous development projects and studies. Furthermore, the team performed market assessments to understand the customer needs. As part of the market assessment, we introduced the teams to *key drivers* and identified *client attitudes*. The team evaluated the tools and techniques in a survey. Figure 15 presents the result of the survey.

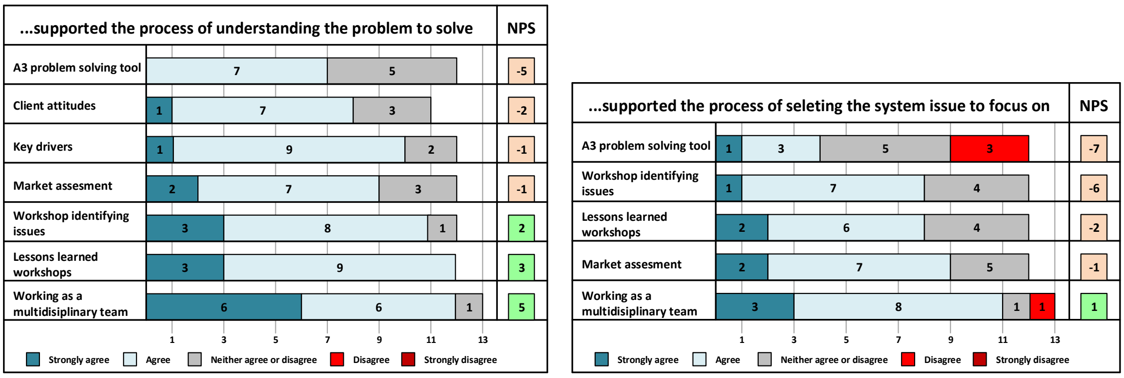

Figure 15: Results from the survey in Article 2 — evaluation of the applied tools and techniques (Article 2 © 2019 IEEE)

The survey found working as multidisciplinary teams to be the key enabler for problem understanding and selecting the system issues. Sharing knowledge between the team members and other company resources is important to explore the problem domain. Informal workshops and discussions support communication and enable the team to understand different perspectives and quickly clarify misunderstandings. The challenge with this communication form is that the team shares the knowledge orally without documenting it properly. As a result, knowledge gained in the discussions is not explicit to those not involved, limiting knowledge transfer.

The survey showed that none of the tools the team applied was good enough to support their reasoning process. The results from the survey and observations show that the team struggles to quantify the design issues and tension in order to make the design decisions. From the article, we find a potential to use conceptual models to support the quantification of issues and knowledge sharing across disciplines.

5.4 Article 3

Title: The Need for Systems Awareness to Support Early-Phase Decision-Making—A Study from the Norwegian Energy Industry

This article presents an in-depth study from the company of research to understand the current awareness of the context of the system and the barriers to improved awareness. From the study and a literature review, we concluded on four aspects to consider when proposing new approaches in the industrial setting. The article applies action research (Checkland & Holwell, 1998) and industry-as-laboratory (Potts, 1993). We gathered the data for this article from seven semi-structured interviews, a survey of 126 engineers, technical documentation, and observation.

The first part presents the results evaluating the current system's awareness in the company. We consider the awareness of system context, operational scenarios, and key drivers. Figure 16 shows the result regarding awareness of the system, Figure 17 presents the results regarding operational scenarios, and finally, Figure 18 shows the results for the key driver awareness.

Firstly, we evaluated the engineer's awareness of the system context and understanding of the interactions with other systems in operation. The study found that the engineers perceive that they have a good understanding of the system context but that the context is not given a sufficient focus in the system development. Further, the results showed that they did not sufficiently understand how their system affects or is affected by the other systems in operation. Similarly, the results in Figure 7 show that the engineers perceive that they do not sufficiently focus on the different operational scenarios in their early-phase work. Finally, the study found that the engineers perceive that they do not have a sufficient focus or understanding of key drivers, as shown in Figure 18. The survey also showed that engineers found balancing internal and external key drivers challenging.

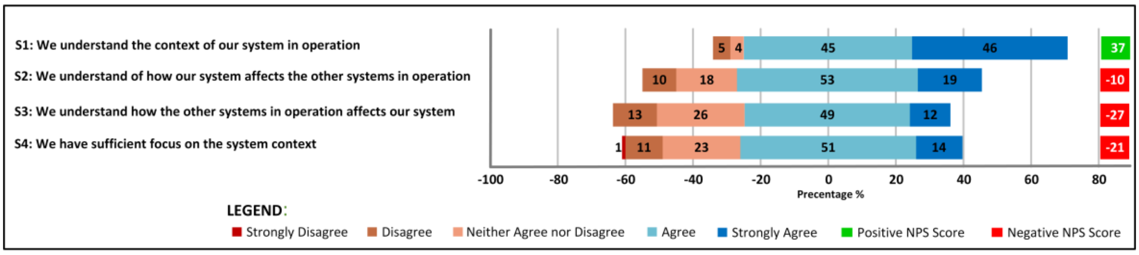

Figure 16: Results from the survey in article 3 — systems context (Article 3)

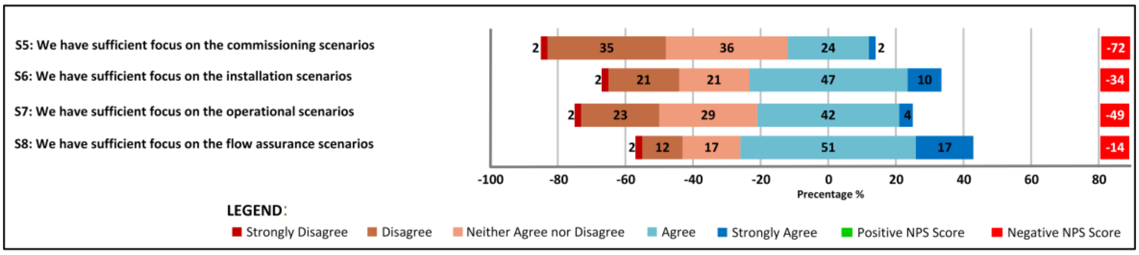

Figure 17: Results from the survey in article 3 — operational scenarios (Article 3)

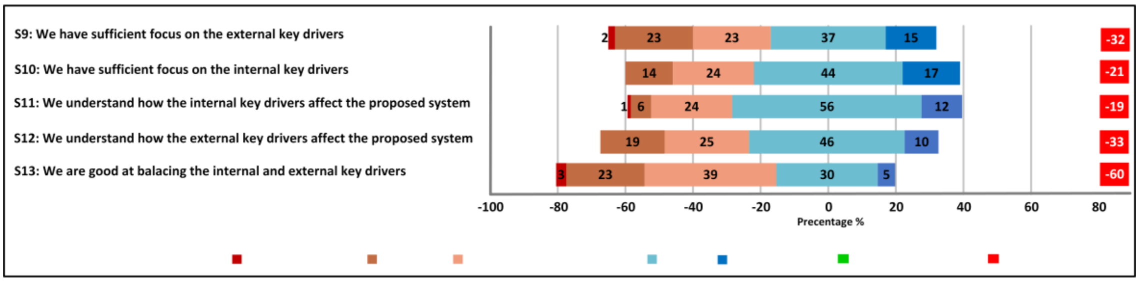

Figure 18: Results from the survey in article 3 — Key driver awareness (Article 3)

From the survey's open-ended questions, we identified the barriers to systems awareness in the company. The main barrier is the *lack of a holistic mindset*. The study shows that the engineers mainly focus on their own systems and give less attention to their role in the system of systems. The second barrier is the *challenge of balancing* *internal and external key drivers*. The study shows a push to utilize the company products and subsystems without sufficiently considering if these fit the customers' needs. The third barrier identified relates to *organizational factors*, as competence is distributed across organizational units and geographical locations, reinforcing the technical silos. The final barrier identified is the *lack of system and operational knowledge.* The study indicates that most engineers are highly competent in their area of expertise, but too few have the overall knowledge of the system.

Based on a literature review of the application of Systems Engineering approaches in the energy industry and the findings from the interviews and the survey, we identified four aspects to consider when developing approaches to the industrial setting. These aspects include *limited use of resources*, *adaptability*, *a low threshold of use*, and *communicating to a heterogeneous group of people*. The *limited use of resources* relates to the nature of the early-phase study phase, being highly competitive, meaning that the company will lose a large amount of the studies they compete for to other supplier companies. This requires approaches that add value without significantly affecting time or cost. *Adaptability* implies that the approaches must be possible to adapt to fit into existing work processes and a range of problems. Implementing new approaches in mature organizations is challenging, even if the approach's value is well known (Kauppinen et al., 2004; Helle, Engen & Falk, 2020). The third aspect to consider is *a low threshold of use*. Implementing systems engineering approaches in the industry is challenged because engineers perceive them as complex and time-consuming (Muller, Wee & Moberg, 2015; Frøvold, Muller & Pennotti, 2017). Therefore, there is a need for methods with a low threshold to quickly reach a sufficient level of concept exploration without requiring too much effort in learning tools or techniques. Finally, the last aspect we identified was *communicating to a heterogeneous group of people*. Cross-functional communication is a challenge in multi-disciplinary teams (Bonnema et al., 2010; Borches, 2010; Boucher & Houlihan, 2008; Heemels & Muller, 2006; Tomiyama et al., 2007). Improving the communication across the stakeholders can improve the understanding of the system and increase system awareness (Muller, Wee &Moberg, 2015; Frøvold, Muller & Pennotti, 2017; Haugland & Engen, 2021).

5.5 Article 4

Title: Conceptual Models to Support Reasoning in Early-Phase Concept Evaluation - a Subsea Case Study

In this article, we applied conceptual models to an actual study in the company to understand how the models could support reasoning during concept evaluation. The research utilizes the research method industry-as-laboratory (Potts, 1993). We collected data by reviewing technical documentation and informal interviews with key resources from the company of research. Additionally, the article presents a literature review on conceptual modeling and decision-making.

The article explores the use of conceptual models to get a mutual understanding and balance conflicting needs. In this case, the management was pushing for a solution that satisfied their company's internal strategy without understanding the long-term impact of their decisions. On the other hand, the engineers were more aware of the long-term impacts but struggled to communicate their knowledge to the decision-makers. We did the study in retrospect to gain insights into how conceptual models could support the reasoning in the early phase.

In the case presented in the article, we explored a study where the field operator asked the company of research to evaluate two alternative solutions for expanding an existing field. Either a horizontal XT (HXT) installed on-template or a vertical XT (VXT) installed off-template and tied back to an existing platform. Figure 19 gives a simplified illustration of the two alternatives. The on-template system with HXT is the solution already installed in the field and the preferred solution of the engineers. On the other hand, the off-template system VXT is the solution preferred by management, representing the company's low-cost solution.

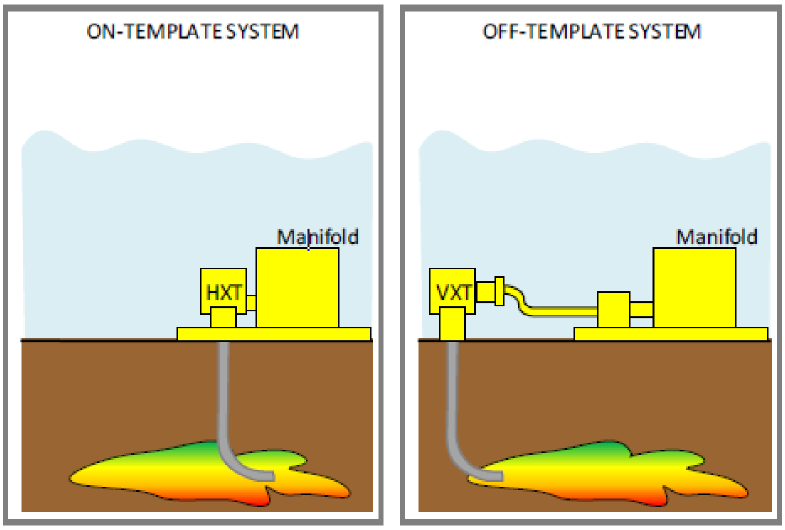

Figure 19: Industrial case: Alternatives considered in concept evaluation (Article 4 © 2021 IEEE)

In the case, we used conceptual models to understand the conflict and communicate the impact of the alternatives across stakeholders. To understand the drivers for the customer and the company, we modeled the key driver using concept maps (Novak & Cañas, 2006). We established the key driver map by reviewing technical documentation and conversations with the lead study engineer. Figure 20 shows the final map. We identified four customer key drivers and four company key drivers from the map. We split the company's key drivers into two categories: the overall drivers related to the company's long-term strategy and the project-specific drivers related to winning this specific contract.

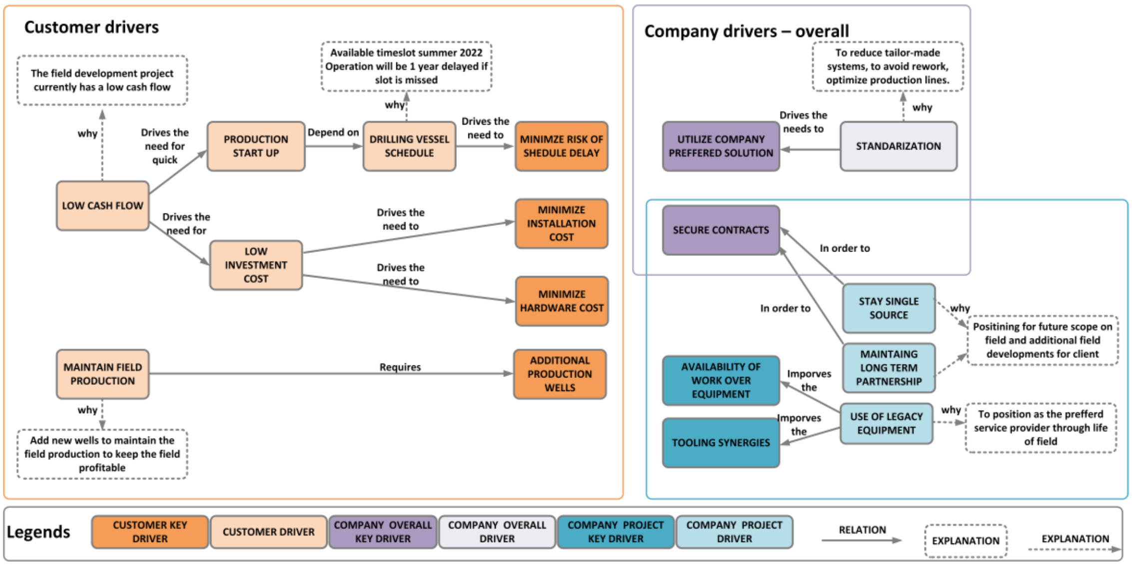

Figure 20: Industrial case: Concept map of the key drivers (Article 4 © 2021 IEEE)

Next, we linked the key drivers to the alternative concepts to identify the tensions. Figure 21 shows the outcome of this model. We found that the company's key driver of utilizing company preferred solutions drove towards choosing the off-template system with VXT, as this was considered the solution that minimized risk and installation cost based on their general knowledge of the system. On the other hand, the project-specific knowledge drove towards an on-template system with Horizontal XT, as the availability of tooling and workover equipment would minimize installation cost and schedule risk. Thus, the tensions are between generic knowledge and project-specific knowledge.

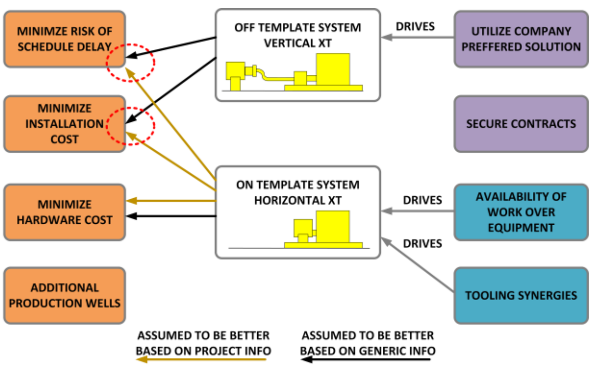

Figure 21: Industrial case: Identification of tensions (Article 4 © 2021 IEEE)

In the next step, we used abstract workflows and timelines to model the drilling and installation phases for the two alternatives. To ensure a common understanding, we started by modeling based on general knowledge of the system. Figure 22 shows the model based on general knowledge.

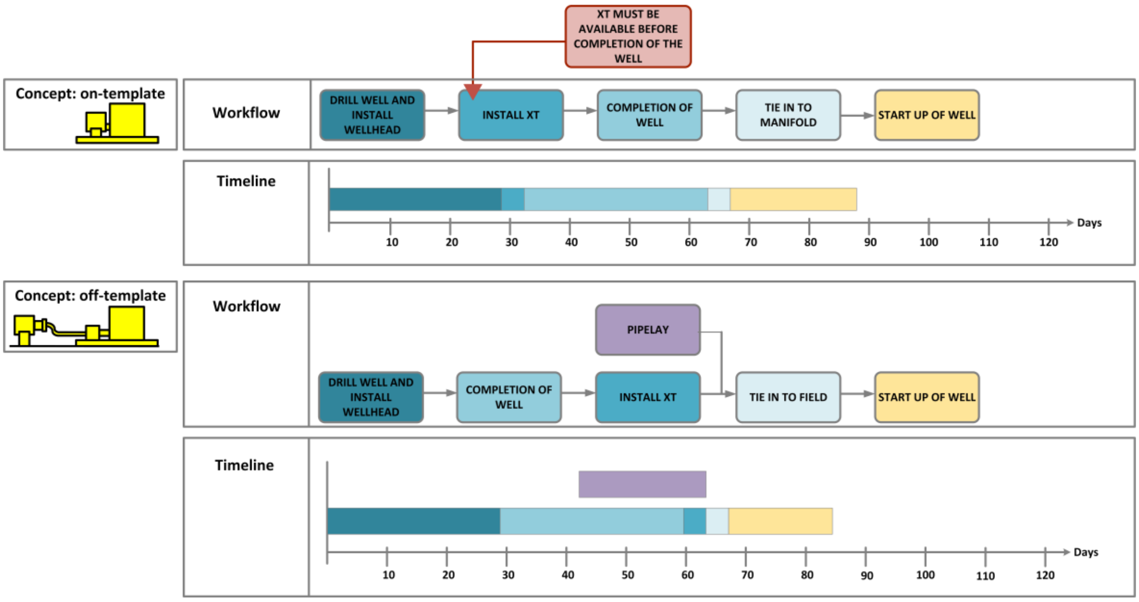

Figure 22: Industrial case: Abstract workflow and timelines based on generic knowledge (Article 4 © 2021 IEEE)

The model shows that the order of the activities in the workflow is different for the two concepts. A horizontal XT requires that the XT is installed before completing the well. Therefore, the XT needs to be ready for operation earlier for the on-template system with HXT than for the off-template system with VXT. The demand for a shorter lead-time of the HXT increases the risk of schedule delay, as indicated in the red rectangle in the model. The other difference in the workflows is that the off-template concept includes a pipelay activity. Since the VXT is installed off-template, it requires pipelines to tie the well into the existing template. Comparing the timelines, we find that the overall timeline for the off-template system is somewhat shorter, as the activity "start-up of well" typically is less scope for the VXT than the HXT. Comparing these two alternative concepts based on general knowledge, the off-template system would be the best choice to minimize the duration of the operation and the risk of delay.

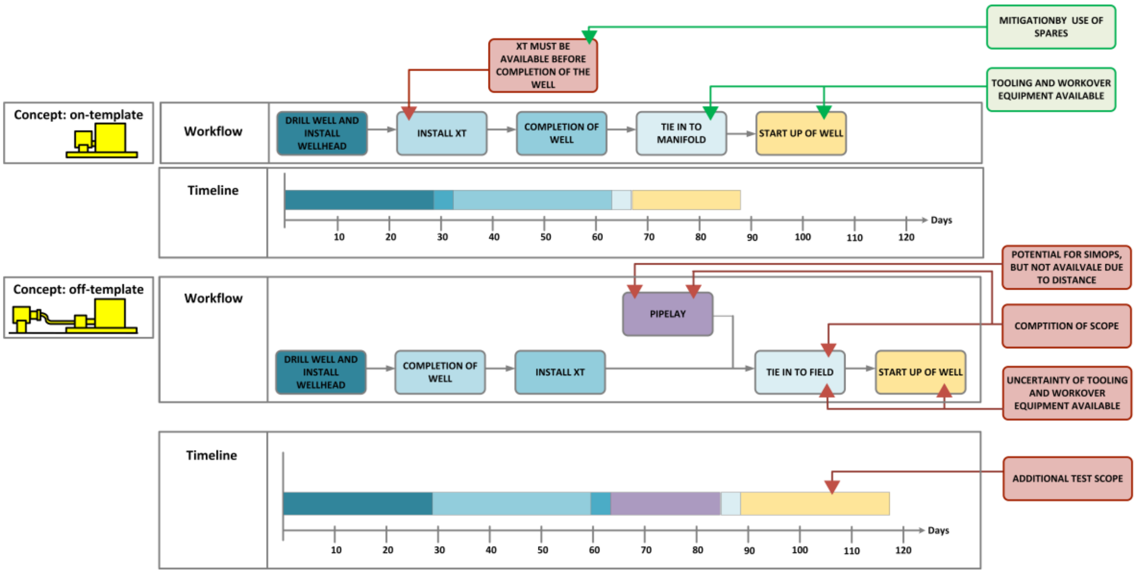

Figure 23: Industrial case: Abstract workflow and timelines based on project-specific knowledge (Article 4 © 2021 IEEE)

Next, we used the model based on the generic knowledge to expand with the project-specific knowledge. Figure 23 shows the updated model. The workflow and timeline for the on-template system were not changed, but mitigations due to the availability of spare parts and existing tooling and workover equipment. For the off-template system, there are several changes to the workflow. Firstly, the generic model assumes that the pipelay activity could be done in parallel with other installation activities. However, operating two vessels in the field simultaneously is not possible due to the short tie-back distance. Consequently, the pipelay activity must happen in sequence with the other activities, extending the overall timeline of the operation. In addition, as this system is new in this field, it will require more test scope in the start-up phase, further increasing the overall duration.

The model in Figure 23 also shows the additional risks for the off-template system, shown as red rectangles. The risk relates to delay due to uncertain tooling availability and additional test work, and the risk of competition on the pipelaying scope. Finally, we documented the findings from the conceptual modeling by including them in the key driver-concept map. Figure 24 shows the outcome of the final step.

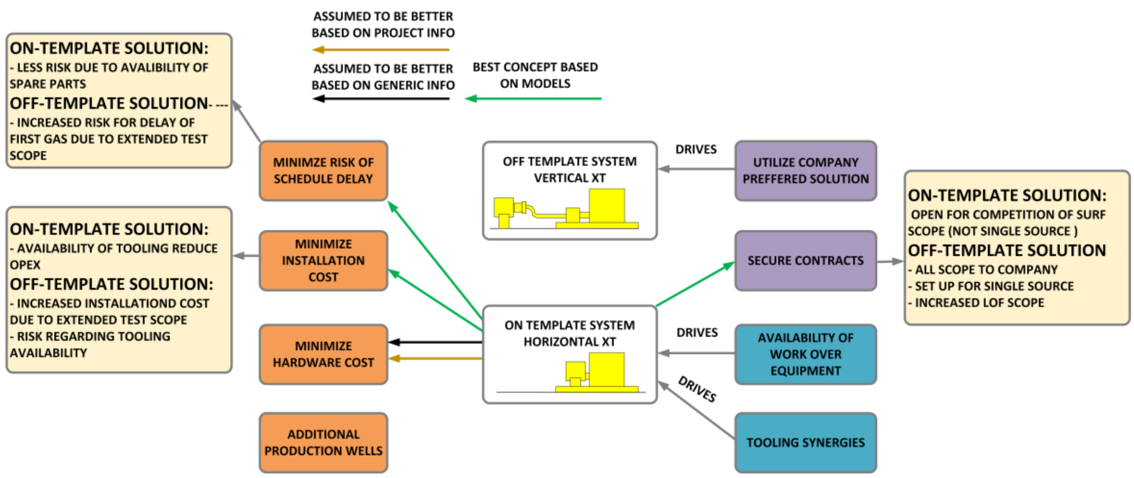

Figure 24: Industrial case: Documentation of the findings from conceptual modeling (Article 4 © 2021 IEEE)

The models presented in this article aim to support the communication between management and engineers. The focus was on improving the understanding of the impact of the decisions made in the early phase and supporting the balancing of conflicting needs. The lead engineer for the study was positive about the systemic approach to the reasoning. He also expressed that the approach would support understanding the system interactions and communicating internally.

In the article, we applied conceptual models. Using such models was based on previous research showing that the engineers in the industry are skeptical of formal modeling (Muller et al., 2015), while the use of conceptual models has shown to be better perceived in the industry (Haugland & Engen, 2021; Muller et al., 2015; Solli & Muller, 2016). The article showed that the conceptual models are appropriate in the concept studies, but there is a need to guide the engineers in applying them in their daily work.

5.6 Article 5

Title: Conceptual Modeling to support System-Level Decision-Making - A Longitudinal Case Study from the Norwegian Energy Industry

This article presents the insights and learnings gained throughout the research. We used the experience from conceptual modeling in the company, including the cases presented in Article 4 and Supporting Article 8, to propose an approach for using conceptual modeling in the daily work in the energy industry to support system-level decision-making. The article also evaluates how the proposed approach and models support the engineers in overcoming the challenges and barriers identified in Article 3. The article applies action research (Checkland & Holwell, 1998) and industry-as-laboratory (Potts, 1993). We collected the data through interactions with practitioners in the industry and a survey in the company to evaluate the approach.

The article presents an approach for using conceptual models to support system-level decision-making. The approach consists of four steps, *map key drivers, identify tensions, elaborate by modeling,* and *document findings.* Figure 25 presents the outline of the approach. We intend the approach to support the concept exploration when the concept evaluation is not straightforward and there is a need to balance the tensions. Together with the approach, we provided guidelines for application and schematic representations of the steps, as shown in Figure 26.

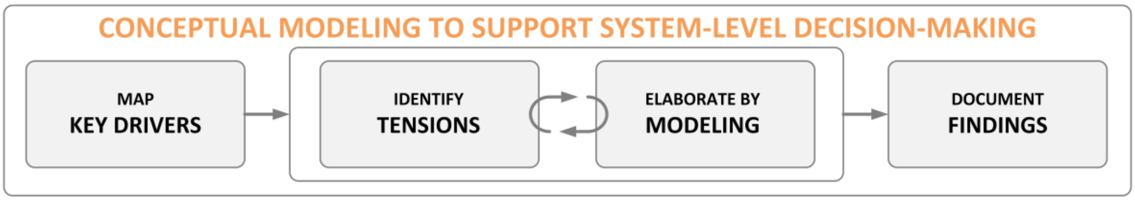

Figure 25: Outline of the approach (Article 5)

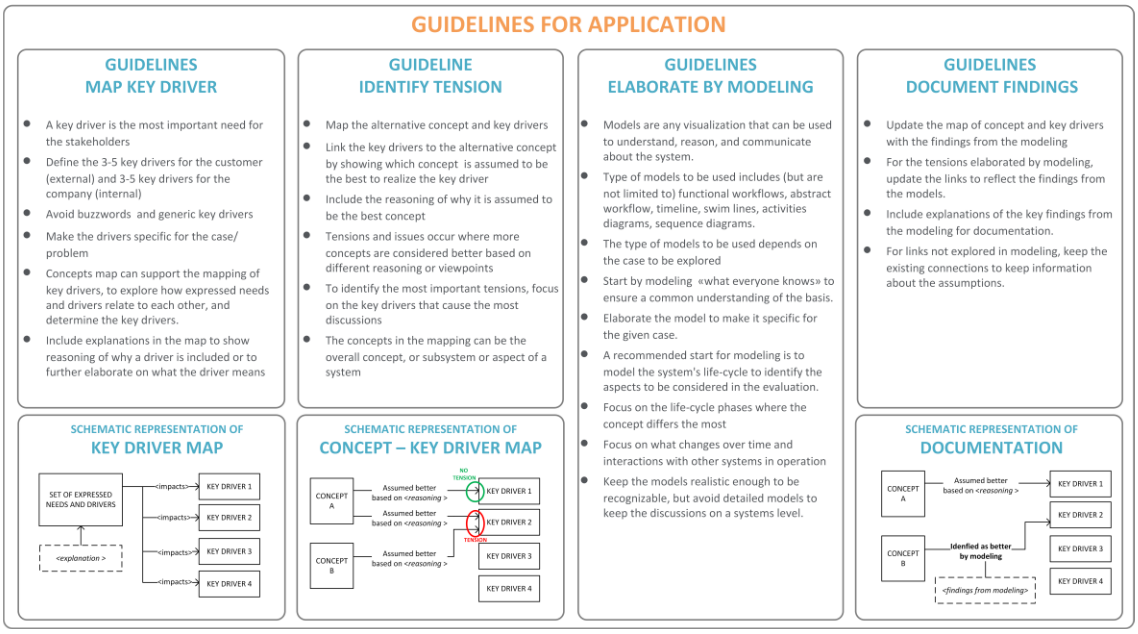

Figure 26: Guidelines for application (Article 5)

The first step is to map the key drivers. If the engineers have already established key drivers, they can be used directly in the approach. However, our interactions in the industry show that the key drivers often are ill-defined in the early phase. Instead, we experience many expressed needs, and drivers are identified, communicated, and used differently throughout the project. Therefore, we propose using concept maps (Novak & Cañas, 2006) to move from the expressed needs to key drivers. Further, we gave guidelines on what a key driver is and how it should be expressed, adapted from (Muller, 2004).

The following two steps are the core of the approach: identify tensions and elaborate by modeling. To ensure the modeling effort is spent where it is most needed, it is essential to understand the most crucial tensions (Heemels & Muller, 2006). In the research clarification, we found that engineers can identify tensions and issues but lack the means to understand which tensions are crucial and should be given attention in the modeling.

To identify the most crucial tensions, we propose to link the concept to the key drivers, indicating which concept is assumed to be the best and stating the reasoning of the assumption. Whenever several concepts are assumed to be the better concept, there is a tension that is a candidate for exploration by modeling. The guidelines give recommendations to support identifying the essential tensions from insights gained in the application in Article 4.

The next step is to elaborate on the tensions by modeling. First, we define a model as any visualization that the engineers can use to understand, reason, and communicate about the system (Muller, 2004). Next, we provide examples of models, including abstract workflows, timelines, swim lines, activity diagrams, and sequence diagrams (Muller, Falk & Syverud, 2019), and emphasize the importance of choosing a model that fits the problem at hand. Finally, to support the choice of model, we provide a set of examples of models and recommendations on when and how to use them. These are domain-specific and based on learnings and insights from conceptual modeling in Article 4 and Supporting Article 8. Figure 27 shows the example of models.

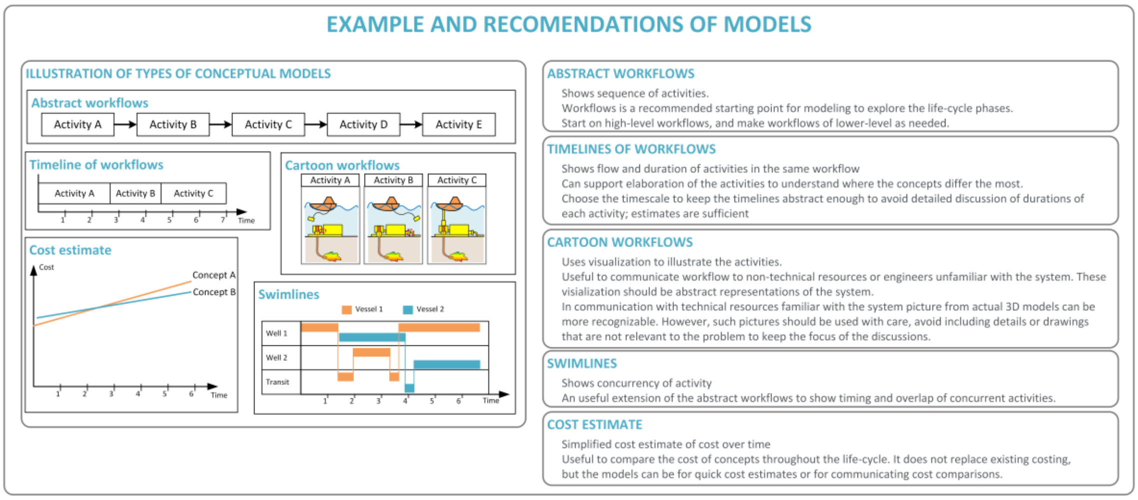

Figure 27: Example and recommendations of models (Article 5)

In the guidelines, we advise on how to get started with the conceptual modeling. As we find that tensions often relate to different perceptions and gut feelings, we guide to model the common knowledge first to ensure a mutual understanding of the basics before going in-depth into the problems. Also, to support the challenge of balancing conflicting needs, we recommend raising awareness of the life-cycle impact focusing on what changes over time.

Identifying tensions and elaborating by modeling is an iterative process. The engineers should use the findings from the modeling to refine the concepts and the tensions. At the end of this process, the final step is to document the findings. The primary purpose of this step is to provide documentation to later project phases of the reasoning of the decisions made and the assumptions made in the study phase. This step is done by linking the findings from the modeling back into the concept-key driver map, highlighting what is elaborated and assumptions.

To illustrate how the approach could be applied, we presented three examples in the article. In the first example, we showed a case where gut feelings and opinions dominated discussions. The example shows how we used abstract workflows in a workshop setting to gain quantified facts about the decisions. The second case gives an example of how the conceptual model can be combined with data from simulations to reason about the impact of the data. The final application example is a short version of the case presented in Article 4.

The article also presents an initial evaluation of the approach in the form of a survey with resources working in the early phase of system development in the company of research. Firstly, we presented the approach and three examples of application through two video presentations of 20 minutes. After the presentation, we asked the participants to answer a short survey. Figure 28-Figure 31 summarize the results of the survey. In addition, the survey asked them to list the top benefits and concerns of the approach, as shown in Table 12.

The survey showed that the engineers were generally positive about the approach and the use of conceptual models. As shown in Figure 28, the engineers find that using the approach in the concept studies supports system awareness, promotes a holistic mindset, and supports balancing conflicting needs. Further, the survey results in Figure 29 and Figure 30 reveal that conceptual models are helpful in communication and knowledge sharing. Especially, they find the models supportive in discussions with non-technical personnel, such as management and commercial. Overall, the respondents find that the approach supports the concept study, and 65% of the respondents stated it is likely or very likely that they will apply it in their daily work.

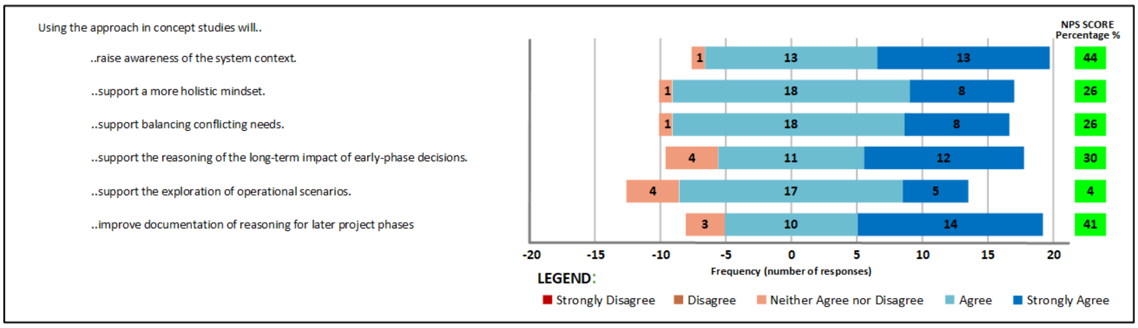

Figure 28: Results from the survey in Article 5 — statements regarding the supportability of the approach (Article 5)

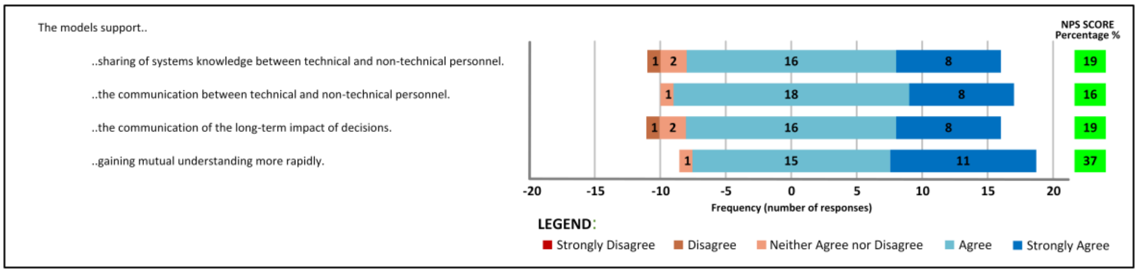

Figure 29: Results from the survey in Article 5 — statements regarding the models' supportability in discussion between engineers and non-technical personnel (Article 5)

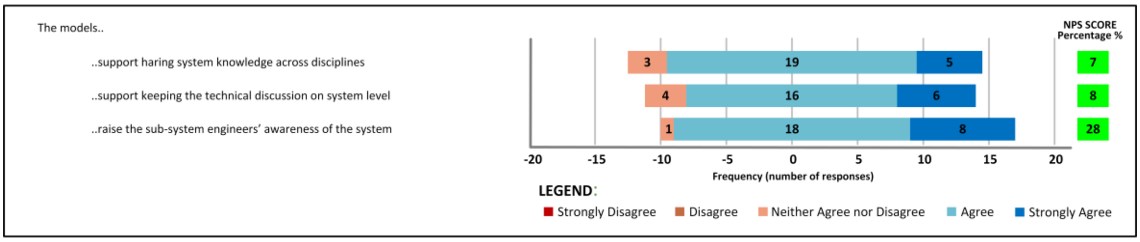

Figure 30: Results from the survey in Article 5 — statements regarding the models' supportability between systems engineers and sub-systems engineers (Article 5)

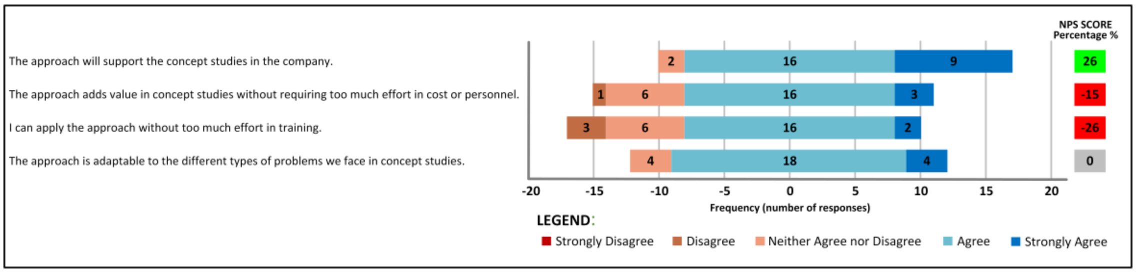

Figure 31: Results from the survey in Article 5 — statements regarding the usability of the approach (Article 5)

Table 12: Results from the survey in Article 5 - benefits and concerns (Article 5)

Reported benefits (number of responses)	**Reported concerns (number of responses)**
Support communication (11)	Implementation (10)
Simplicity (8)	Key driver identification (8)
Raise system awareness (7)	Need for systems understanding (5)
Visual (6)	Added work (5)
Documentation (5)	Risk of oversimplification (3)
Common understanding (3)	Require resources (3)
Systematic (3)	Training (3)
Engagement (3)	

The survey shows there are concerns related to the implementation. In particular, the results show that the respondents are concerned with the effort required to provide value, the level of training required, and the approach's adaptability. The company is a large organization with several existing processes and tools. Implementing new approaches in mature organizations is challenging (Kauppinen et al., 2004; Chami & Bruel, 2018). Therefore, in defining the approach, we have focused on the approach’s adaptability. The respondents recognize simplicity as one of the main benefits, which will ease the application in daily work. Even if several highlighted simplicity as a benefit, others raise this as a concern due to the risk of oversimplification. The level of detail in the conceptual modeling is a reoccurring challenge. Balancing the need for abstracting with the need for being specific is a crucial challenge in conceptual modeling. One needs to conceptualize to gain insight while including the details to be specific.

Further, several express concerns that applying the approach requires engineers with extensive system knowledge. We recognize this concern; however, we claim this concern is valid independent of the approach used in the early phase. Applying the conceptual models can support the company in more effectively utilizing their knowledge in the concept studies. This is supported by the survey results, as the respondents find supporting communication and a common understanding, and raising system awareness as benefits of the approach.

The article intends to extend the knowledge of conceptual modeling in the energy industry. The article concludes that the conceptual models can increase the systems engineers' knowledge and experience of modeling to improve the awareness of the system in the concept studies. Further, proposing a structured approach will support the engineers in the industry to apply conceptual modeling in their daily work.

6 Synthesis

The energy industry is going through rapid changes. At the starting point of this research, the industry had recently experienced severe downturns. The downturns gave the industry an increased focus on simplification to reduce costs and lead time. In the aftermath of the downturns, the industry has adapted to new business models and increased cooperation across the supply chain. During our research, severe changes in the global environment have also impacted the industry, such as the energy transition and the digital transformation. All the changes require the actors in the industry to cope with increasing complexity, both in terms of the technical system and regarding business and organization.

In the research clarification phase, presented in Articles 1 and 2, we found a lack of focus on the stakeholders and the life cycle needs, particularly the operational needs. This finding coincides with other research in the domain, identifying a lack of focus on operational context (Allaverdi et al., 2014; Tranøy & Muller, 2014). In the in-depth study presented in Article 3, we found that the engineers have knowledge of the operations but that the operational context and the role of the system in the field development are not given sufficient focus in the early phase. Before the downturns, often referred to as the golden era, the energy industry's spending was record high (Garcia, Brandt & Brett, 2016). In this period, the focus was on fast delivery rather than low cost. Following the downturns, there was a shift in the industry, which required the suppliers to take more responsibility for their offerings (Engen, Mansouri & Muller, 2019). To take this responsibility, the system suppliers need to utilize their system knowledge efficiently, focusing on the operational context and balancing out conflicting needs.

The concept studies in the energy domain are highly competitive and fast-paced, requiring the suppliers to get to a good enough level of decisions with a minimum investment in hours and cost. Therefore, modeling is crucial in this phase to support concept exploration, and the systems engineering body of knowledge provides tools and approaches to support this activity. However, the energy domain is immature in adapting systems engineering approaches (Helle, Engen & Falk, 2020). Muller and Falk (2018) stated that for approaches to be applicable in the energy industry, they need to adapt to their circumstances and needs. Article 3 concluded on four aspects that should be considered when developing and implementing approaches in the early phase of the energy domain. Considering these aspects is essential to make approaches relevant to the context and make them recognizable to the engineers working in the industry. The four aspect includes *use of resources*, *adaptability*, *low threshold of use*, and *communicating to a heterogeneous group of people.*

Considering these four aspects, we applied conceptual modeling in different contexts in the company. Previous research has shown that the practitioners in the domain respond well to such approaches (Muller, Wee & Moberg, 2015; Solli & Muller, 2016; Løndal & Falk, 2018), but they need support to apply the models in their daily work. Article 4 demonstrated how the conceptual models could balance conflicting needs and communicate across diverse stakeholders. Further, the article showed how to identify the tensions to understand where to focus the modeling effort. Using the learnings from this case study and the insights from applying conceptual modeling in the daily work in the company, we proposed an approach for conceptual modeling supporting system-level decision-making in the concept studies. Article 5 presented this approach. The approach consists of four steps, *map key drivers, identify tensions, elaborate by modeling,* and *document findings.* Together with these four steps, we provided guidelines and examples to support the engineers in applying the approach in their daily work.

Article 5 also presented an evaluation of the approach. The evaluation showed that the engineers were positive about the approach and about using conceptual models in the early phase. In our research, we have seen that the use of visual models lowers the threshold for participating in discussions. The evaluation survey identified both the visual format and the models' positive contribution to active engagement in discussions as benefits of the approach. A strength of the approach is the simplicity. The approach is tool independent and can be applied independently of existing company processes. This allows the engineers to apply it in their daily work when it is suitable for their tasks, without requiring a full adaption of the whole organization. Our research suggests that this flexibility increases the chances of adoption in the industry.

The evaluation in Article 5 showed that several see the simplicity of the models also as a concern, worrying that the models are not detailed enough. In (Haugland & Engen, 2021), we found that the company resources tend to prefer to illustrate the system components using detailed 3D models rather than using abstract models. Interactions with the industry reveal a tendency of quickly going into detail, considering detailed realization instead of focusing on the system's functionality. It is essential to balance abstraction and details to gain system insights. Muller et al. (2019) stated that when modeling, one needs to conceptualize to gain insight while including the details to be specific. From our experience from interactions with practitioners, we see that once the engineers get familiar with the conceptual modeling, they get less concerned about the simplicity and see the benefits of abstraction. We believe that the approach can support the engineers in familiarization with conceptual models and raise the discussion from details to system level.

The approach focuses on conceptual models to support the concept exploration. We have developed this approach in a context that is document-centric, with limited implementation of model-based system engineering tools and approaches. In this context, we find conceptual models to be a good starting point for getting familiar with the concept of modeling and raising awareness of a model-based mindset. The conceptual models we present are not thought to be an alternative to the more formal models. Instead, we believe it complements the formal modeling. Our approach supports the exploration of the system design alternatives in the early phase. The outcome of this exploration will be the design decision that defines the systems architecture, which can be incorporated into a formal system model.

The energy domain is going through a digital transformation (Lu et al., 2019) leading to an increased focus on using data to support decision-making. In our interaction with the industry, we observe that they already perform detailed simulations in the early phase, generating large data sets. These are often discipline-specific and quickly go into a very detailed level. Bratvold and Begg (2008) have also observed that the industry quickly turns to detailed analysis and stated that the industry follows a philosophy that "*given sufficient computing power, we can build a detailed enough model of the decision problem to enable us to calculate the right answer.*" The outcome of these simulations is only data. To transform data into insights, engineers also need to utilize human knowledge. The conceptual models can support the transition of data into insights. Example 2 in Article 5 exemplifies this, using data from a discipline-specific analysis combined with costing to the reason for the overall system impact.

The approach presented in Article 5 synthesizes the insights and learnings from four years of research in the industry. The evaluation showed that the engineers in the company are, in general, willing to try the approach in their daily work. However, the engineers have concerns about the training and effort needed to apply conceptual models. We believe that the structured approach can support the engineers in getting familiar with conceptual modeling, making it a part of their current work practice. Further, we contend that applying the approach will increase the systems engineer's knowledge and modeling experience and, as a result, improve the system's awareness in the concept studies.

7 Validation

This chapter discusses the validity of the research presented in the thesis, following the approach described in Section 4.5. First, we evaluate the trustworthiness of the research by discussing credibility, transferability, dependability, confirmability, and reflexivity. Finally, we evaluate the researcher's bias and reactivity and how we have mitigated the threat of bias during the research.

7.1 Trustworthiness

7.1.1 Credibility

Credibility refers to the confidence that can be placed in the truth of the research findings (Korstjens & Moser, 2018). To evaluate the credibility, we have employed the eight-point checklist by Maxwell (2012). The following discusses how we have considered each element during our research.

1) *Intensive, long-term involvement.* A key element in this research is the long-term involvement with industry practitioners. We have collected data through four years of interaction with the company of research. Also, the researcher was employed in the company for ten years prior to starting the research. The in-depth knowledge of the organization and the company culture supported us in the interactions with the practitioner and the data collection. In addition, we were co-located at each industry location for 12-18 months, allowing us to build trust and understand the project language and behavior in-depth.
2) *"Rich data."* We have focused on collecting data from diverse sources and contexts to get different perspectives and an in-depth understanding throughout the research. For example, we have collected people's perceptions and behavior through observations, interviews, and surveys. In addition, we have reviewed

static information in the form of technical documentation to get another perspective. In the interviews and survey, we have recruited respondents with diverse backgrounds, experiences, and roles in the company to ensure multiple perspectives.

3) *Respondent validation.* We have actively shared our research with the respondent during the research to ensure we have interpreted the data collected correctly. This sharing was mainly done through daily interactions, sharing our findings with resources in the company. In addition, all research publications have been shared with technical and commercial resources. Finally, we have done several presentations for technical resources in the company and industry, which validated that our findings were recognizable.
4) *Intervention.* The research applies Industry-as-laboratory, in which intervention with the industry is an important aspect. During the research clarification and the descriptive study I, we sat in a development project in the company, giving us the possibility to have a daily intervention with the engineers. During the prescriptive study, we co-located with the department working with concept studies, allowing us to observe and intervene with several ongoing studies. The possibility of following several studies and being a part of the daily discussions in the group supported our reflections in the prescriptive study. We were mainly located at the home office during descriptive study II due to the global Covid-19 pandemic. Therefore, we primarily interacted with the engineers through digital meetings, which limited the intervention in this phase. To adapt to this setting, we selected the video format to present the approach to the engineers. The video format gave us a valuable evaluation of our work but limited the interaction and possibility to adapt the approach according to the practitioners' needs and inputs.

5) *Searching for discrepant evidence and negative cases.* We performed literature reviews to evaluate our findings compared to cases reported in the literature to search for discrepant evidence. Further, we have included open-ended questions in our data collection to allow the respondents to express their opinions and concerns. In the data analysis, we have used the negative responses to reflect on the expressed needs and improve our understanding.
6) *Triangulation.* In the research, we actively applied method triangulation and data triangulation. Method triangulation refers to the use of several methods in the data collection. Data triangulation refers to using multiple data sources in time, space, or person. We have collected data through interviews, surveys, observation, document review, and literature review in the research. In addition, we have followed projects with different characteristics during the research to gather observations in different contexts. Further, we recruited candidates from different business segments and roles to get diversity in the respondents in the interviews and survey.
7) *Numbers.* Qualitative data is the primary source of data in our research. We have, when possible, used numbers to quantify our findings. For example, we use numbers in the form of Net Promoter Score analysis. Further, we used numbers in the document reviews and the coding of open-ended questions to count repeated findings.
8) *Comparison.* Performing the research within only one company has limited our possibility of performing multiple cases for comparison. We have mitigated this by comparing several cases in the company and by comparing our cases to the literature. The lack of comparison limits the possibility of generalizing our findings. In order to improve the validity of this research, future research should apply and evaluate the proposed approach in other companies

7.1.2 Transferability

Transferability refers to the degree to which the results of our research can be transferred to other contexts (Korstjens & Moser, 2018). Further, they recommend providing *thick descriptions* to ensure the transferability of the research. We have provided a detailed description of the research context in our research. Our research focuses on the energy domain, which is not well described within systems engineering literature. Therefore, we have provided descriptions of the energy domain, the processes, and the subsea system, in all publications and this thesis to clarify the context in which we have performed the research. Further, we have in the research given detailed descriptions of how and where we have collected our data to provide information on the context of the data collection.

7.1.3 Dependability

Dependability considers the stability of the research findings (Korstjens & Moser, 2018). Further, they stated that in order to ensure dependability, the research should transparently describe the research steps taken from the start of a research project to the development and reporting of the findings. In Chapter 4, we have described our research approach in detail. Further, we have clearly described the research method and the data collection in all our publications. The descriptions allow for externals to evaluate the quality of the research.

Furthermore, we have published all appended and supporting articles in conferences and journals that have a peer-review process, which has given an external review of all results. We have also actively used peer-reviewing, sharing the results with colleagues before publications, to reflect on the findings. After the research clarification phase, a mid-term review of the Ph.D. research was held with external accessors. The mid-term allowed the accessors to audit and critique the research process and audit the validity of the research.

A threat to the dependability of our research is that only the candidate has been analyzing the raw data. To mitigate this threat, the candidate has reviewed the findings with the academic supervisors to identify inconsistency and bias. Further, we have used triangulation and quantification to reduce the risk of this threatening the research's validity, as described in section 7.1.1.

7.1.4 Confirmability

Confirmability refers to the degree to which the findings of the research study could be confirmed by other researchers (Korstjens & Moser, 2018). Moon et al. (2016) state that to achieve confirmability, the researcher must demonstrate that the results are clearly linked to the conclusion in a way that can be followed and, as a process, replicated. To ensure confirmability in our research, we have structured our research following Design Research Methodology (DRM) by Blessing and Chakrabarti (2009). Using a recognized methodology to describe our research enables others to understand and reproduce the process we have used in our research. In section 4.1, we have described how we have applied the DRM, the primary outcome from each stage of the research, and how they relate to the results presented in the appended articles.

Further, to support the confirmability of the research, the research should clearly show the research philosophy followed and the approach for theory development. We have used the research onion (Saunders, Lewis & Thornhill, 2019) to position our research, and this is described in Section 4.3.4.

7.1.5 Reflexivity

Reflexivity refers to the critical process of self-reflection about the role of the researcher. A strategy for ensuring reflexivity is a diary, examining one’s conceptual lens, assumptions, preconception, and values and how these affect research decisions (Korstjens & Moser, 2018). Throughout the research, we have kept a logbook. In the logbook, we have recorded our observations in the industry and our reflections on the observations. The logbook notes are a mix of handwritten and electronic notes, depending on the situation. The logbook contains company-sensitive information, the logbook is kept confidential, and the reflections are only shared with the academic supervisors. Throughout the research, we have actively discussed the reflections with the academic supervisors to evaluate the quality of self-reflection.

7.2 Researcher Bias and Reactivity

We have used action research in our work, collecting mainly qualitative data. There are two broad threats to the validity of such research: *researcher bias* and *reactivity*. Throughout the research, we have actively worked to reduce the risk of bias and reactivity by collecting rich data, triangulation, and quantifying data, as described in 7.1.1. Further, we have actively performed member checks and peer-review to validate the findings and identify if biases have impacted our analysis.

The candidate was employed in the company of research for ten years prior to starting the Ph.D. research. This knowledge of the company and its work practice was advantageous in the research clarification phase, giving us an in-depth understanding of the context. Further, knowing the company culture, language, and behavior was supportive when collecting the data. Finally, in the interview settings, we found that the fact that the candidate was employed in the company built trust with the interviewees, allowing them to speak more openly about the challenges in the company. However, the close relationship between the candidate and the company of the research increase the risk of bias. Specifically, the experience of working in the company has affected the candidate's lens on the challenges. To mitigate this bias affecting the research, we have used the logbook and actively discussed findings and reflections with the academic supervisors.

There is a risk of the respondents being more optimistic about the researcher's proposal because they are familiar with the researcher. In the research, we have recruited respondents from different geographical and organizational units using the company's organizational charts in the data collection. Further, we used the group managers to ensure we had included all relevant personnel. We applied this recruitment process to mitigate the selection bias and ensure we also recruited respondents not familiar with our research.

In the research, we have been working closely with the practitioners, being a part of the daily work in the projects we have followed. The intervention allows the researcher to understand the situation in-depth and observe how proposed tools and approaches support the work. The approach we have proposed in the research is an outcome of the insights and learning we have gained from applying conceptual modeling and other approaches in different teams and projects. Consequently, several practitioners have been exposed to elements of our approach before the final evaluation, which could impact their perception. To reduce the impact of reactivity in the final evaluation, we invited all employees in the systems engineering group to the evaluation survey. These resources are distributed in several organizational groups and across multiple geographical locations. The wide recruitment of respondents ensures that we also include resources that the researcher has not impacted. Further, we compared the responses from those who have been impacted and those who have not to evaluate if the responses were significantly different.

8 Conclusion

This section presents the conclusion of the thesis. First, we revisit the research questions. Next, we present the contribution of this thesis, and finally, we describe the limitation and propose further work.

8.1 Revisiting the Research Questions

The energy industry has the last decade gone through significant changes. The reoccurring low oil prices have forced all actors in the industry to make drastic cost reductions, shifting the focus from hardware cost to total cost of ownership. In addition, the ongoing energy transition set new requirements for all the actors in the industry in how they operate and to develop new technology.

To cope with the challenging market, several actors in the industry look towards systems engineering. Through a four-year longitudinal case study in a system supplier in the energy domain, we have researched to support architectural reasoning in the early phase of system development to improve the company's offers. In the research clarification phase, we did two case studies in the company. The first study examined the existing engineering process and the emerging needs in the early phase studies. As a result, we identified the need to improve awareness of the systems context and the life cycle needs. The second study followed a system development project to understand the existing work practice. The study found that the engineers lacked the tools to support problem exploration and knowledge sharing. Based on the research clarification, we defined three research questions. The following sections revisit the research questions.

RQ1: What are the challenges and needs for improving systems awareness in the early phase of system development in the subsea industry?

Engineering a good constituent system requires awareness of the encompassing system and its operational context. To explore the systems engineer's awareness of the system, we conducted an in-depth qualitative study in the company of research (Engen, Falk & Muller, 2021b).

a) *How aware are system engineers of the encompassing system and the operational context of their system during the early phase?*

Regarding RQ1 a), the study presented in (Engen, Falk & Muller, 2021b) showed that the systems and sub-systems engineers in the company of research perceive that they know the system context. However, even if they have the knowledge, they do not sufficiently consider the context in the early phase as this is not a focus. The study finds that the engineers recognize that they do not sufficiently understand how their system affects or is affected by the other systems in operation. Furthermore, the study shows a lack of focus on the operational scenarios in the early phase.

b) *What are the barriers to exploring and understanding the system and operational context in the early phase?*

To address RQ 2b), the research coded and analyzed the survey results to identify the prevalent barriers to exploring the system context in the early phase (Engen, Falk & Muller, 2021b). The research identified the lack of a holistic mindset as the main barrier. Technical silos are a challenge in the energy industry, and it is also a challenge in the company of research. The silos lead to a focus on the sub-system and component level and a limited focus on the overall system. Further, the research found that lack of systems knowledge limits the awareness of the system context. The competence within the technical silos is high, but too few have sufficient knowledge of the overall system.

Finally, the research found that the challenge of balancing external and internal key drivers is a barrier. Too often, there is a push from management to utilize a company preferred solution without sufficiently understanding the long-term impact of this choice. Technical resources have the system knowledge needed to understand the long-term impact better but struggle to communicate this knowledge.

c) Which aspects are important to consider when developing and implementing approaches to improve systems awareness in the early phase?

Finally, to address RQ1 c), the research combined insights from applications in the industry and literature review to understand what to consider when developing methods and approaches to be adopted in the industrial setting (Engen, Falk & Muller, 2021b). Previous research in the industrial setting has shown challenges in getting engineers to adapt the techniques in their daily work. Therefore, the researchers propose a set of aspects to consider for developing approaches applicable in the industrial setting. The aspects proposed include *limited use of resources, adaptability, low threshold of use,* and *communicating to a heterogeneous group of people.*

RQ2: How can conceptual models support the early phase of system development in the subsea industry?

Our research finds that there is a great potential for using the conceptual models in the industry to improve the engineer's systems awareness. In particular, the research found that conceptual models can support engineers in the reasoning process, improving the quality of system-level decisions.

a) How can conceptual models improve the system awareness of the engineers in the early phase?

To answer RQ2 a) the researchers have, throughout the research, applied conceptual models in the daily work in the company. These cases are presented in (Engen, Falk & Muller, 2021a; Engen, Muller & Falk, 2022). The research found that the conceptual models support communication and knowledge sharing. Especially, the models are supportive in discussions between technical and non-technical personnel. Further, the research found the models to support a mutual understanding and help the engineers reason about the problem and the long-term impact of decisions.

b) How could an approach for using conceptual modeling to support system-level decision-making in the energy industry look?

Regarding RQ2 b) (Engen Muller Falk, 2022) synthesized the learnings and insights gained from application in the industrial setting to outline an approach for using conceptual models to support system-level decision-making. The approach consists of four steps, *map key drivers, identify tensions, elaborate by modeling,* and *document findings.* Further, the research provides guidelines to support the engineers in applying the approach in the industrial setting. The core of the approach is identifying tension and the elaboration of modeling. The early phase in the energy industry is highly competitive and fast-paced, requiring the suppliers to get to a good enough level of decisions with a minimum investment in hours and cost. Therefore, identifying tensions supports the engineers to focus their modeling effort on where it matters the most. Further, the research provides guidelines for using conceptual models to explore the tensions, support a common understanding, and move from gut feeling to facts.

RQ3: How applicable is an approach for conceptual modeling for the early phase of system development in the subsea industry?

One of the main objectives of the research was to support practitioners in the energy domain in applying conceptual models in their daily work. The research presented an initial evaluation to understand how the engineers in the company perceive the approach proposed in the research.

a) How do the engineers perceive the usefulness of the approach?

To answer RQ3 a), the researchers presented the approach and its application to systems engineers in the company of research (Engen, Muller & Falk 2022). Further, a survey to explore their perception of the approach following the presentation. Most respondents believe the approach will support the concept studies and are optimistic about applying it in their daily work. The respondents find the approach to improve systems awareness by supporting a holistic mindset and balancing conflicting needs. In addition, the respondents found that the approach support communication, highlighting the simplicity and visual format as the main benefit.

b) What are the challenges for the engineers to adopt the approach in the industrial setting?

Regarding RQ3 b) (Engen, Muller & Falk 2022) found the main challenge to be the implementation in the organization. The concerns relate to getting a commitment for the approach in a global organization and adding work to the existing processes. The study also reveals concerns regarding the training needed to apply the approach and get into modeling.

8.2 Contribution

This thesis contributes to the Systems Engineering Body of Knowledge by providing insight into the current systems engineering practice in the energy domain and the industry needs in the concept phase. Further, the thesis contributes with insight into the application of conceptual modeling in an industrial setting.

We observe in the industry that Systems Engineering is often perceived mainly as a process for project execution. However, through the long-term interactions and active participation in the daily work, the research has contributed to an increased awareness of other aspects of systems engineering in the company of research. Further, the research contributes to the industry by providing a systematic approach, guiding industry practitioners in applying conceptual models in their daily work.

Table 13 summarizes the theoretical and practical contributions of the articles appended to this thesis.

Table 13. Summary of the appended articles' theoretical and practical contributions

Article	Theoretical contribution	Practical Contribution
1 and 2	Provide insights into the current work practice in the early phase in the energy domain and the need to raise system awareness.	Article 1 provides a system engineering process that practitioners can apply in the concept studies. In addition, the outcome from articles 1 and 2 directly impacted the company's business process, adding the identification of stakeholder needs and key drivers as a step in the concept studies.
3	Add to the knowledge on the challenge of systems awareness in large-scale multidisciplinary system deliveries. Further, it contributes with insight into aspects that should be considered when applying new approaches in the domain.	The results pinpoint the challenges in the company and can contribute to raising the engineer's awareness of the system.
4	Add to the knowledge base on knowledge of how conceptual modeling supports concept evaluation in the early phase.	Provides the practitioners with guidance on applying conceptual modeling in their concept studies.
5	Add to the knowledge base on how conceptual modeling can be used in the early phase to support decision making Add to the knowledge base on how conceptual modeling can support communication and knowledge sharing	Provides the practitioners with an approach to support concept evaluation. In addition, the guidelines, recommendations, and examples of applications provide practitioners with guidance on applying conceptual models in their daily work.

8.3 Limitations and Recommendations for Future work

We have based our research on action research and industry-as-laboratory. Such research approaches are commonly used for systems engineering research to gain an in-depth understanding of the industry's challenges and implement the results from the research in the industry. However, the approaches carry the risk of researcher bias. To reduce this risk, we focused on long-term involvement, used triangulation, and collected rich data from multiple sources.

A major challenge in action research is the generalization of research findings. We have conducted our study only in one company, which allows us to explore the problems and barriers in-depth. However, as the study only considers one company, the results cannot be generalized across the industry. Therefore, we have shared our findings through interactions with practitioners in the energy industry, and based on the feedback, we consider the findings to be recognizable and applicable to other companies. However, we cannot claim that the results are valid for other research contexts than the one we described in our research.

In order to generalize the research findings, further research should evaluate the applicability and validity of the research findings in other contexts. Mainly, it is relevant to evaluate the approach's applicability in the early phase concept studies in other actors in the industry. However, we believe that the approach can also support concept exploration in other domains, and further research should explore to which extent the insights from this research could be transferred to other contexts.

A grand challenge in applying conceptual modeling in the early phase is balancing the need for abstracting with the need to be specific. Our research provides insight into this challenge from four years of intervention with practitioners in the energy domain. Further research should explore this challenge in more detail and develop means to support engineers in conceptualizing system concepts to improve system understanding and knowledge sharing. Additionally, it should be further explored how the conceptual models can be used more efficiently together with the data produced in simulations and analysis to reason about the system.

We propose using conceptual modeling in the early phase, as it can support the rapid exploration of concepts under uncertainty without requiring significant investment in time or cost. However, in later phases of the system development, more formal systems modeling approaches can be more applicable to support the documentation and communication of the system. Further research should look at how the conceptual and formal models could be used together in a model-based environment.

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Appendix 1

The following documents presents the information regarding the research that was provided to the participants in the surveys and interviews. The following documents are included

1. Information to participants, Survey, Article 2
2. Information to participants, Survey, Article 3
3. Information to participants, Interview, Article 3
4. Information to participants, Survey, Article 5

Participation in research project "System architecture and design in oil and gas industry"

Purpose of the project

The proposed research aims to investigate how systems engineering methods can be applied in early project phases to improve the system understanding.

Project responsible

Siv Engen

Why are you selected?

The research gathers experience data from employees in the company. Selection of participants are based on your role in the organization.

What does it mean to for you to be involved?

You will be asked to take part in survey

If participating it will require you to fill out a survey. This will take approximately 20 minutes. The survey will mainly focus on your experience in the company. The data will be registered electronic.

Participation is volunteer

It is volunteer to take part in the project. If you choose to participate, you can later withdraw your consent without giving any reason. All data collected will be anonymized. It will not have any negative affect if you choose not to take part or withdraw your content.

Your privacy

We will only use the information about you to the purpose as described in this letter. We will treat all data confidential and according the privacy regulations. The data will only be accessible for the researcher and the academic supervisors. To ensure no unauthorized access to your personal data, your e-mail, role, department and experience will be replaced by a code that is stored on a list separate from the remaining data. The information will be stored on a server only the researcher can access.

After the research is finalized

The research is planned completed 01.04.2021. After the research is completed, the data will be anonymized.

Your rights

As long as you are identified in the data material, you have the right to:

- Get insight to the personal information registered about you
- To have your personal information corrected
- To have your personal information deleted
- To get a copy on your personal information
- To complain to the personvernombudet or Datatilsynet about the treatment of your personal data

What gives us the right to treat your privacy data?

We treat data about you based on you consent.

On behalf of the University South East Norway, NSD - Norsk senter for forskningsdata AS, has evaluated that the treatment of privacy data in this project is according with the privacy regualtions.

How can I find more information?

If you have question to the study, or want to use any of your rights, please contact

- Siv Engen, USN/TechnipFMC, siv.engen@usn.no
- Personvernombud at USN. Paal Are Solberg personvernombud@usn.no
- NSD – Norsk senter for forskningsdata AS,
  Mail: personvernombudet@nsd.no, Phone: 55 58 21 17.

Med vennlig hilsen

Siv Engen
Project responible

Participation in research project "System architecture and design in oil and gas industry"

Purpose of the project

The proposed research aims to investigate how systems engineering methods can be applied in early project phases to improve the understanding of the stakeholder needs and transfer of knowledge between project phases.

Project responsible

Siv Engen

Why are you selected?

The research gathers experience data from employees in the company. Selection of participants are based on their project participation or their role in the organization.

What does it mean to for you to be involved?

You will be asked to take part in

- Survey ☐

Survey:

If participating it will require you to fill out a survey. This will take approximately 5 minutes. The survey will mainly focus on your experience with the methods applied in the project team. The data will be registered electronic.

The survey will mainly focus on your experience with the methods applied in the project team.

Participation is volunteer

It is volunteer to take part in the project. If you choose to participate, you can later withdraw your concent without giving any reason. All data collected will be anonymized. It will not have any negative affect if you choose not to take part or withdraw your content.

Your privacy

We will only use the information about you to the purpose as described in this letter. We will treat all data confidential and according the privacy regulations. The data will only be accessible for the researcher and the academic supervisors. To ensure no unauthorized access to your personal data, your name will be replaced by a code that is stored on a name list separate from the remaining data. The information will be stored on a server only the researcher can access.

After the research is finalized

The research is planned completed 01.02.2021. After you research is completed, the data will be anonymized.

Your rights

As long as you are identified in the data material, you have the right to:

- Get insight to the personal information registered about you
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Project responsible

Siv Engen

Why are you selected?

The research gathers experience data from employees in the company. Selection of participants are based on their project participation or their role in the organization.

What does it mean to for you to be involved?

You will be asked to take part in an, interview

Interview:

If participating it will require you to participate in a semi structured interview. This will take approximately 30 minutes. The interview will mainly focus on your experience with application of system engineering and knowledge transfer in your project. The interview will be documented by recording and transcriptions.

Participation is volunteer

It is volunteer to take part in the project. If you choose to participate, you can later withdraw your consent without giving any reason. All data collected will be anonymized. It will not have any negative affect if you choose not to take part or withdraw your content.

Your privacy

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Project responible

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Purpose of the project

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Project responsible

Siv Engen

Why are you selected?

The research gathers experience data from employees in the company. Selection of participants are based on your role in the organization.

What does it mean to for you to be involved?

You will be asked to take part in survey

If participating we ask you to watch two video presentations, in total 20 min. Next, we ask you to fill out a survey regarding the usefulness of the presented approach. This will take approximately 10 minutes. The data will be registered electronic.

Participation is volunteer

It is volunteer to take part in the project. If you choose to participate, you can later withdraw your consent without giving any reason. All data collected will be anonymized. It will not have any negative affect if you choose not to take part or withdraw your content.

Your privacy

We will only use the information about you to the purpose as described in this letter. We will treat all data confidential and according the privacy regulations. The data will only be accessible for the researcher and the academic supervisors. To ensure no unauthorized access to your personal data, your e-mail, role, department and experience will be replaced by a code that is stored on a list separate from the remaining data. The information will be stored on a server only the researcher can access.

After the research is finalized

The research is planned completed 01.01.2022. After the research is completed, the data will be anonymized.

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If you have question to the study, or want to use any of your rights, please contact

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Med vennlig hilsen

Siv Engen
Project responsible

Article 1

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Application of a System Engineering Framework to the Subsea Front-End Engineering study

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Abstract. This article applies formal system engineering methods in early-phase concept studies in the subsea oil and gas industry to identify early-phase needs, and reduce late-phase design changes. The oil industry is changing, demanding more cost efficient, flexible, and modularized systems. In order to improve their offering, suppliers within this industry are turning towards the systems engineering domain. To better understand the problem, we investigated the engineering processes at the supplier, went into details of technical project reports, and interviewed main stakeholders at the supplier. Based on our research we propose to adjust the early phase of the project execution process for the company, and adapt to a system engineering framework. At an early stage we recommend using unformal models to communicate decisions and to set up a foundation for applying more formal models in the later phases. A case study from field development illustrates the new process and methods. Some of these systems engineering methods have already been adopted in the company to improve the front-end engineering studies.

Introduction

Domain. For the suppliers of subsea systems to the oil and gas industry, the subsea front-end engineering study represent the innovative pre-sales period. Yet, the lifecycle of an offshore oil and gas field starts several years earlier, by the discovery of oil and gas trapped in a reservoir. After detailed geological and economical evaluations the oil company decides if the field should be developed or not. If it is decided to develop, oil companies conduct reservoir simulations to optimize the field development scenario and suggest the initial number and location of wells. Next the oil and gas field moves into the field development phase, and the scope is split into several subsystems, one of them being the subsea system. A subsea system comprises of pipelines, robust valves, manifolds, and control systems. Its main function is to transfer the oil and gas safely and efficiently from the bottom of the sea up to a surface facility. Per (Leffler, Pattarozzi, & Sterlin, 2003) subsea technology has a critical and sometimes dominant economic role in the oil and gas industry's portfolio of new field developments.

Suppliers of subsea oil and gas system are typically the ones performing subsea field development studies. Based on the input from the oil company the suppliers each develop several concepts, and evaluate these per the premises of the study. At the end of the study, the suppliers provide concepts to the oil company together with a description of the technical solution and an overview of cost and schedule. When the suppliers have delivered the suggested concepts, the oil company are to decide if they are to move forward with the field development or not. If the oil company are to continue the field development, they decide on which concept to use, and the field development moves into tender and execution phase.

Case. Over the last years, the cost level in the subsea industry has increased rapidly. A cost report from the Norwegian national petroleum technology strategy shows that the subsea cost has tripled in the period 2005-2013 and that the increase in investment is significant compared to the activity increase (OG21, 2015a). Since 2014 the oil price has dropped significantly which makes the field development even less profitable. Combining low oil prices with cost increases, makes it challenging to develop profitable fields (Bergli & Falk, 2017). The cost report (OG21, 2015a) claims that the industry should target a cost reduction of 50% to meet the future market. An important reason for cost overruns in the industry is the lack of identification of the early phase needs (Tranøy & Muller, 2012; Callister & Andersson, 2015). It is evident that there is a need to increase the system engineering work in the field development studies, to ensure proper identification of early phase need.

Problem. There is a gap between how the field development study is performed and how the systems engineering is adapted in later stages of a subsea delivery project. How can we improve the field development study process? We claim that applying a more formal system engineering framework to the field development process, would make the process more efficient, and reduce the risk of missing important early phase needs.

Finding. In this paper, we investigate the current process for field development with a major global subsea provider by interviews and analysis of former field development studies. We identify shortcomings related to identification of stakeholders and stakeholder needs and documenting the decision process. We propose a modified process, including more extensive work to identify stakeholders and understand the stakeholder needs. Also, we propose to introduce models to document the evaluation and decisions made, to improve communication to the later project phases.

Company of research. The company being target for this research is a global supplier of equipment to the oil and gas industry. We have conducted our research within a Norwegian department specializing in subsea production systems. To avoid confusion of terms, the equipment supplier is hereby called “company”, and the oil and gas company is hereby called “client”.

Research methodology

The research is conducted using the research method industry-as-laboratory (Heemels & Muller, 2007). The research has focused on how field development studies historically have been conducted and the challenges with performing studies in today's market. For research of the historical work we have studied the existing process as described in the Company's Business Process Management System. In addition, we have performed analysis of 30 previous conducted study reports in the time span 2013-2017. For research to identify challenges with concept study today and how the prediction for the future study work is we have performed interviews with key resources from field development, tender and project execution groups. Based on the analysis and research we have developed a new process for future studies by combining the existing process in the company and the system engineering framework (Sols, 2014). Finally, we have performed a case study using the new process to illustrate the use and show example of how the models can be included.

Background

Systems engineering application and theory

According to (INCOSE, 2014) systems engineering is defined as "an engineering discipline whose responsibility is creating and executing an interdisciplinary process to ensure that the customer and stakeholder's needs are satisfied in a high quality, trustworthy, cost efficient and schedule compliant manner throughout a system's entire life cycle." Several approaches exist for system engineering. One process model commonly used is the Vee Model (Forsberg & Mooz, 1991). According to (INCOSE 2015), the Vee model is "a sequential method used to visualize varying key areas for the SE focus, particularly during the concept and development stages". The Vee-model focus on validation of the stakeholder needs during development phase and the need of verification plans. (Sols, 2014) proposed in 2014 a new System Engineering Framework, which intention is allowing the transformation of identified needs or opportunities to solution. He emphasizes that this is a framework and not a process, and claims using the term process indicates a linearity in the execution of a series of steps, which offers little latitude or flexibility of implementation, while a framework is more agile, flexible, and versatile, and leaves more room to adapt to the problem at stake (Sols, 2016).

Modelling

According to the INCOSE Handbook (INCOSE, 2015), stakeholders of the system engineering life cycle have used models and simulations for some time to check their own thinking and communicate their concepts to others. The handbook lists several types of model and emphasize that the choice of model for a phase in the system's life cycle should be "fitness for purpose", meaning it depends on the intended use, the characteristic of the system of interest and the level of model accuracy. Among the types of models, they include unformal models, which can be simple drawings or words. These can be useful, but according to the handbook the unformal models need to meet certain expectations to be considered within the scope of modeling for system engineering. More formal models are also listed, this can be logical or conceptual models, which represent the relation between the elements in the system. The Incose handbook states that many types of models can be used as part of a model-based approach. Model based system engineering is an emerging direction of system engineering, which are replacing the more traditional document based system engineering. The benefits of MBSE over the document-based includes traceability and transparency of the evolving design, improved design completeness, and improved knowledge sharing (Do & Cook, 2012). Incose SE Vision 2020 (INCOSE, 2007) defines Model Based System Engineering as "the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." In the literature, there are many views of what MBSE is and which methodology and tools should be used. But all emphasis the importance of modelling and per Bonnet et. al. there is a rather shared conviction between systems engineering practitioners that MBSE brings benefits and is the only way forward to cope with the growing complexity of systems to design (Bonnet, Voirin, Normand, & Exertier, 2015).

Systems engineering in subsea industry

The focus on system engineering in the oil and gas industry is growing, and the establishment of the Incose Oil and Gas working group in 2016 is a proof of this. The Norwegian subsea industry is increasingly applying systems engineering process to ensure success of their projects (Mjånes, Haskins & Piciaccia, 2012). Wee and Muller (2016) states that the supplier company typically uses a project execution model built on the Vee model. An example of application of the system engineering process to the subsea development is given by Yasseri (2014).

Recent research has found several shortcomings in the industry that could be improved by proper system engineering work. (Callister & Andersson, 2015) claims that requirement non-conformance and system failure is identified too late in the engineering process. (Tranøy & Muller, 2012) shows that the late design changes are one of the main reasons for the cost overruns in the subsea industry analysis. They illustrated this by a case study performed of a subsea system delivery, showing that 74 % of the late design changes could be prevented by early phase need analysis. Several articles predict model based system engineering (MBSE) as the way to go for the future subsea industry, among these (Bergli & Falk, 2017). However, there is a limited research on actual usage of MBSE in the industry. (Baker, Ferraioli & Pereira, 2016) gives one contribution which shows how to model a retrofit subsea system using a bottom up approach. (Muller, 2015) claims that attempt of introducing more formal methods in the subsea industry are often met by skepticism, and approaches that are more formal are perceived as time-consuming and not applicable. A lot of research within the system engineering in the subsea domain recently is related the use of illustrative models and methods (Solli & Muller, 2016) investigated the used of illustrative ConOps within the subsea domain, and their research states that the use of illustrative ConOps together with a high-level Pugh matrix can serve as a trigger for discovering opportunities and constrains not initial considered. They also concluded that it shows potential when used as tool in communicating qualities of conceptual solutions between project member and stakeholders.

Current state of field development in company

The company model for field development

The company execution model is described in the Company's Business Process Management System (BPMS). The field development is performed in the phase called acquire order, under the activity *"perform sales"*, and this forms the basis for the tender and project execution. The process for field development studies is given in *"perform field development study"*, as illustrated in Figure 1.

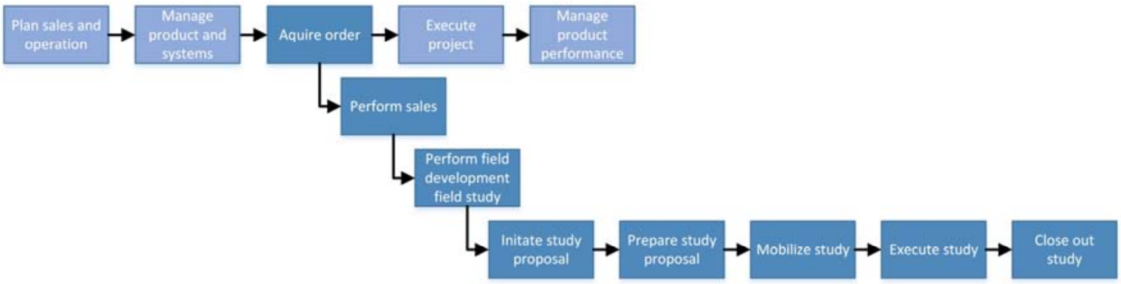

Figure 1: Existing process for field development studies within company

The *"perform field development study"* process start off with *"initiate study proposal"*, were the main activity is to define the strategy and to decide if study should be executed or not. Next follows *"prepare study proposal"*, where the purpose is to capture the client needs and to create a scope of work that is accordance with these needs. Then the study set up in *"mobilize study"*. Following this is *"execute study"* and this process starts with describing study requirements, using the contract and the client's needs and requirements as input. As part of this activity the evaluation criteria and weights to be used for evaluation of the concept are populated. The next step in "*execute study"* is to identify system solutions, in which several concepts are developed together with the discipline experts. Next the concepts are evaluated, and it is specified that this shall be done using an evaluation matrix. This evaluation shall be subject for a review meeting which also shall conclude on preferred concept and verify that this is in accordance with the client needs and requirements. Once the concept is chosen, the technical documentation for this system shall be developed, and new review meeting shall be held to check that the selected concept fulfills the contract and requirements. Finally, the cost and schedule shall be developed and a study report shall be issued to client. The study ends in the activity *"close out study"*. The technical activities in the company *"perform field development study"* can be summarized as shown in Figure 2.

Figure 2: Summarized field development process

Review of company process for field development

To investigate the use of the development process in the company, we performed study of 30 reports from field developments study performed in the time span 2013-2017. From the analysis, we find that all the analyzed studies follow the company process. The key findings from the analysis can be summarized as:

- **Client is the only stakeholder.** We see in the reports that the client provides all the needs and requirements used in the study and that client is treated as the only stakeholder. Only in 1/30 studies additional stakeholders is directly included in the concept evaluation. In this case the operator is included in the complete concept study.
- **Client ask for solution, not concept.** Out of the 30 studies analyzed, we found that in most cases the client has decided on the concept for field development, and company is only asked to evaluate different systems or products. Only in 8 of the 30 reports the company is asked to develop a concept for the field development.
- **No standard for documentation.** The reports follow the same format, but there is no standard for what shall be included in the reports or the level of detail for documenting evaluations and decisions performed in the study.

To understand the need for the future field development we conducted interview with 3 key resources from field development, tender and system engineering group in company. These all have central positions in their respective groups, each holding more than 10 years of experience from the industry. The interview was organized semi-structured, all of them where gather for an unformal conversation, where they were invited to raise their opinion about the future market and trends. The key findings from this interview can be summarized as follows:

- **Clients asking for concept.** It is a trend in the market that the client ask company to do a full concept study of the field, without having dictated the solution up front.
- **Integrated contracts.** The contracts are more often integrated contracts, meaning the studies shall cover both subsea and surf system.
- **Shorter time span.** In the current market, it is seen that the time from study and tender to project execution is significantly reduced. This makes the time from decision of concept to commission short, which is challenging for the long lead items.

In addition, we conducted a more in-depth interview with the resource from system engineering group, regarding the handover from study and tender to project, based on the experience from the project executed the last 5 years. This interview confirmed the findings from the analysis of previous study reports, and the challenge of documentation of evaluations and decisions was highlighted as a key concern.

From the analysis and the interviews, it is found that the current process is very dependent on the client identifying all early phase need before requesting the study. However, this seems not to be the case in most projects. For the studies where client asks for a complete concept study, is especially important that the company have an internal process to identify the stakeholder and stakeholder needs. From the analysis of the study reports it is evident that there is no standard for how to document the concept study. The one writing the report has in depth knowledge of what is done, and what's obvious for the writer is not properly documented. The reader picking up the report in the next phase lack this knowledge, and will not be able to understand all evaluation and decisions made in the concept study. This leads to misunderstandings, which increase the risk of rework in later phases.

A new process for field development study

System engineering framework

(Sols, 2014) proposed a new framework for system engineering for the complete system life cycle, from identification of need or opportunity to system phase out. Figure 3 summarizes the first activities in the framework up to the selection of the preferred design concept.

The System Engineering Framework starts by the identification of a need or an opportunity, which is translated into a problem formulation. Next the stakeholders should be identified and be given as input to the concept of operation (ConOps). Identification of stakeholders and ConOps is iterative processes, as showed with the dashed arrows in Figure 3. Having concluded on the stakeholders and the ConOps, next activity is to identify the stakeholder requirements. Then a validation should be done to ensure that the translation from problem formulation into stakeholder requirements is done correctly and that the set of stakeholder requirements fulfill the initial problem. If it is found to be incomplete, one should go back to the stakeholder requirements or ConOps and perform activities needed to fulfill the original problem. Once the stakeholder requirements are complete, the next activity is to identify design concepts and finally preferred design concept is selected.

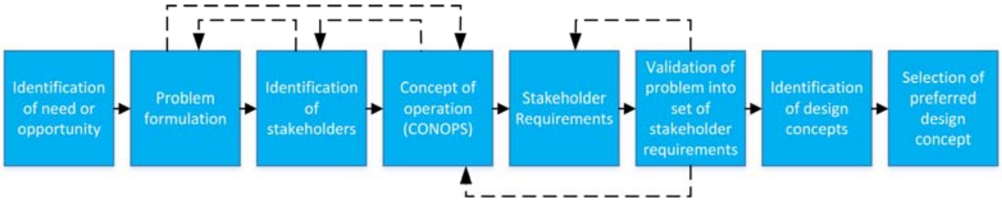

Figure 3: System Engineering Framework

Combined process for field development

The major difference between the system engineering framework as given in Figure 3 and the process used within company as summarized in Figure 2 is the initial activities. The framework has initial activities to understand the initial need or opportunity and identify the stakeholder before the stakeholder requirements is established, the company process start directly with identification of needs and requirements. The company process assumes that the client is doing the initial identification of needs, and provides company with a complete set of needs and requirement. Another difference is that the framework includes a validation if the problem is correctly translated to stakeholder requirements. The corresponding activity in the company process is to populate the evaluation criteria and weights, which is reviewed together with client to ensure the correct understanding of the initial problem. The framework continues with activities to further develop the system, and next step would be to develop system requirements. The company process has a closing activity to check solution towards needs and requirements, since the system are not further developed in this phase. This ensures that the selected system solution fulfills the initial need.

As seen from the analysis and interviews there is a need for the company to take more responsibility to understand who are the stakeholders for the subsea system and identify their needs. Therefore, we suggest modifying the company process to include the initial steps from the system engineering framework, but with some adaption. We have chosen to combine the identification of stakeholder and ConOps to one activity, as these are done through several iterations, and the sequence of these two activities, should be done as beneficial for the study. We have also chosen to use "stakeholder needs and requirements", rather than just stakeholder requirements. Some of the studies are done in a very early phase or with an extremely brief time span, and for these only including on the stakeholder needs is the sufficient level of detail. The proposed new process is illustrated in Figure 4.

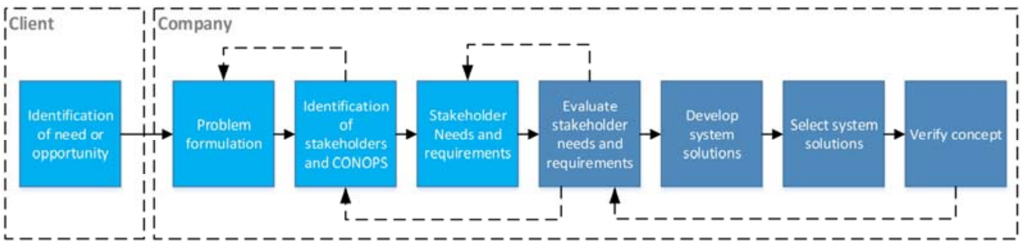

Figure 4: Suggested new process for field development

Another challenge with the field development process discovered in the analysis is that it lacks good documentation of the decisions and evaluation preformed, which could lead to rework in the tender and execution phase. To mitigate this, we propose to include unformal models to document each stage of the process to improve communication through all project phases. In the following a description of each activity in the new process and the suggestion of models and methods to be used is given.

Identification of need or opportunity. The process starts by client identify a need or opportunity and start up the front-end engineering study by sending a request to the company.

Problem formulation. Based on input from the client, the first activity for the company is to formulate the problem. This is a crucial step to ensure that company understand the problem correctly and to communicate this understanding to all personnel involved in the study. We suggest doing this activity by making a graphical representation of the system of interest illustrating the boundaries and input from the client. This should be used to derive the actual problem to be solved.

Identification of stakeholders and concept of operation. Next activity is to identify stakeholders and make a Concept of operation. The most common technique for identifying stakeholders are brainstorming, but brainstorming alone is found to not be sufficient for identifying all relevant stakeholders (Salado, 2013). To improve the stakeholder identification, we recommend combining the brainstorming with an illustrative ConOps, as described by Solli et al (Solli & Muller, 2016) to understand the system needs throughout the system life cycle. Identification of stakeholder and ConOps should be done as an iterative process. The outcome of this step should be a model showing stakeholder and ConOps as illustrated in the case study.

Stakeholder needs and requirements. Next step is to identify the stakeholder needs and requirements. The input from the client is given as input to the study, but as seen in the analysis these tends to be a mix of stakeholder requirements and detailed system requirements. This activity should be used to understand which of the requirements given from the client is actual stakeholder requirements and to identify additional high-level requirements for the other stakeholders. The level of detail of the requirements are strongly depending on the time span of the study, but it is important that the activity is carried out to some extend for all studies. According Sols (2014) the consequences of poor defective formulation of requirements in early phase of the life cycle will be evident as the project proceeds and that they can be dramatic. The work for (Tranøy & Muller, 2012) and (Muller, Wee, & Moberg, 2015) supports that this is a problem in the subsea industry. Due to the nature of the project life span of a subsea development, it expected that the stakeholder needs and requirements are changing from the study phase to the tender and execution phases. Therefore, it is important to document the origin of all requirements. To ensure that the information is retained we recommend showing the relation of the stakeholders and the derived needs and requirements with a simple illustrative model as shown in the case study.

Evaluate stakeholder needs and requirements. Once the needs and requirements are identified, they should be evaluated to ensure they are corresponding to the initial need and problem formulation. We suggest that this is done by translating the requirements into a set of evaluation criteria and give each of the criteria a weight to indicate its importance. The client should evaluate the list of criteria and weightings to ensure that it matches their needs and expectation.

Develop system solutions. Next activity is to develop several concepts for system solutions. This activity is most often done by brainstorming, based on the experience of the field development engineers executing the study.

Select system solution. When the concepts are developed, they should be evaluated to select the best system solution. We recommend doing this by a Pugh Matrix (Pugh, 1991) with weighting of the criteria (Lønmo & Muller, 2014).. All criteria are scored for each of the cases, with the scores S, S+ or S-. S means it is neutral compared to the others, while S+ means better than and S- means worse than. The recommended use of the weighted Pugh Matrix is illustrated in the case study.

Verify concept. Having chosen the preferred concept, the final activity in the process is to verify that the concept is in accordance with the stakeholders needs and requirements. This is done by linking the functionalities and features for the chosen concept to the need or requirement it fulfills. To do this, the model of the stakeholder needs and requirements made in earlier step, should be updated to include functions and features, as illustrated in the case study.

Application, case study

This section presents a cases study were the new processes is applied to a field development study. The case study is a randomized field, called Donald, and the data provided for this field represent typical data provided by client to the subsea suppliers in a field development study.

Input from client. The client has requested a field development study for an oil and gas field in the Norwegian Sea. Client has given a field layout showing the location of 7 wells, 3 oil producers, 2 gas producers and 2 water injectors. The field is located 16 km from the infrastructure. In addition, client has given the functional requirements for the field, such as production rates, pressures, temperatures, water depth and reservoir depth.

Step 1. Problem formulation. The first step in the method is to formulate the problem. To do this, we made a sketch of the requirement and boundaries given in the input from client to identify the system of interest as circled in grey in Figure 5. Using this representation of the system together with the input from client, it was defined that the problem to be solved can be defined as "Bring oil and gas from the reservoir to the infrastructure with an efficient and low-cost system solution".

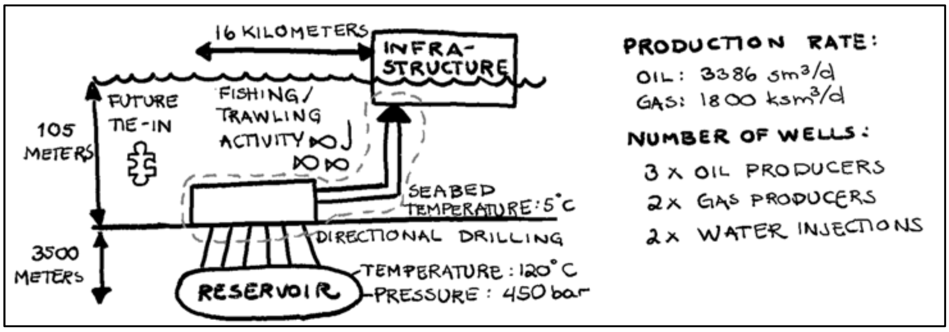

Figure 5: System of interest.

Step 2. Identify stakeholders and concept of operation. The next step is to identify stakeholders and the concept of operations (ConOps). As described this is an iterative process, and the end state of the process is shown in Figure 6. In this case study the stakeholders and ConOps is only developed for the top level, but as needed each of these phases could be broken down to several levels of ConOps to get an even better identification of stakeholders.

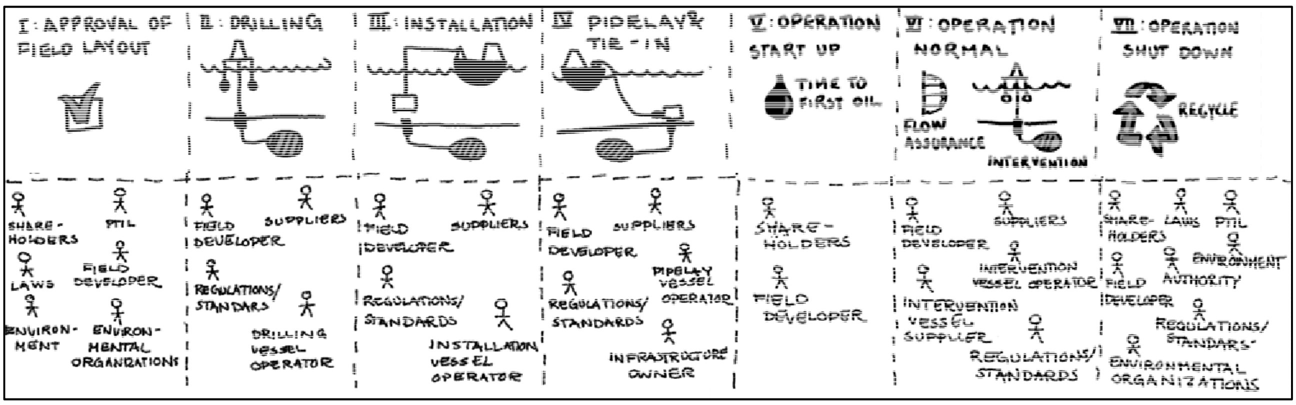

Figure 6: Top level ConOps for the field development with stakeholders

Step 3. Identify stakeholder needs and requirements. Once the stakeholders for the study were elected, we identified their needs and requirements, as shown in Figure 7. This model illustrates the high-level needs, and links them to the different stakeholders. The same type of model could be used to show the stakeholder requirements, by linking them to stakeholder.

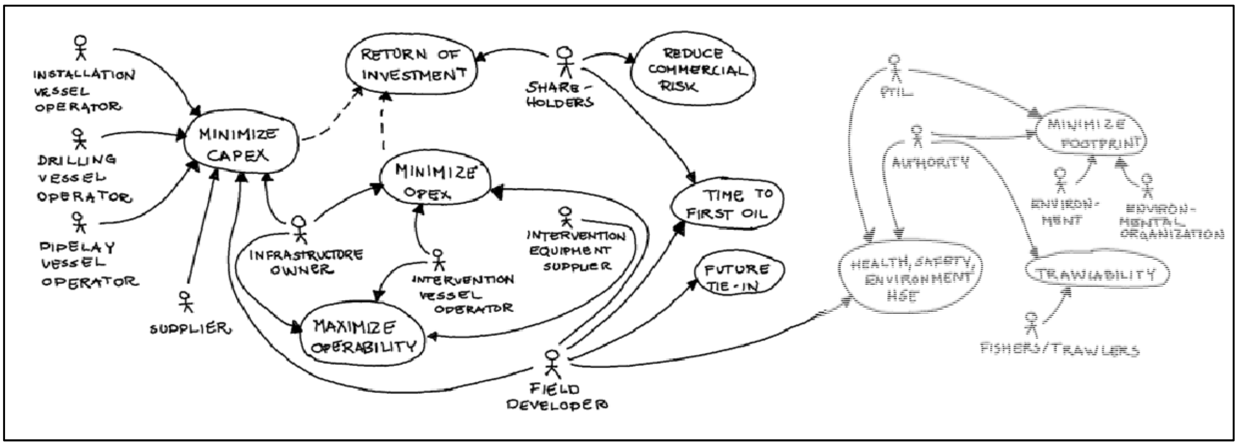

Figure 7: Stakeholder needs linked to stakeholders

Step 4. Evaluate stakeholder needs and requirements. Next step is to translate the needs identified in Figure 7 to a set of evaluation criteria. From the problem formulation, it is seen that the main need is to have a low-cost system, and to capture this some of the needs identified Figure 7 is broken down in several factors influencing the total cost of the concept, while others is kept as is. All criteria have been given a weighting, to indicate the importance of the criteria. The complete list of criteria and weighting is given in Figure 8. This list is discussed and modified together with client before continuing the process, to ensure a mutual understanding of the initial need.

Criteria		Weight
Minimize CAPEX	Cost of equipment	High
	Cost of drilling	Medium
	Cost of installation of equipment	Medium
	Cost of installation of pipelies	Medium
	Cost of tie in and connection	Low
Minimize OPEX	Cost of operations	High
	Cost of intervention operations	Low

Criteria		Weight
Maximize operability	Flow assurance	Medium
	Pigging	Medium
Time to first oil	Phased development	High
Commercial risk	Technology readness level	Medium
HSE		High
Minimize footprint		Low
Owertrawability		Low
Future tie in		Medium

Figure 8: Evaluation criteria

Step 5. Develop system solutions. Five different concepts for system solutions for the field were developed, namely

- Concept I: 6 slots manifolds + water injection satellites
- Concept II: 2 x 4 slot manifolds
- Concept III: Satellite wells
- Concept IV: Multi-bore X-mas Tree (XT) with subsea water processing system
- Concept V: Subsea on slim legs.

A brief explanation of each concept including the field layout drawings and description of the equipment used is given in Appendix.

Step 6. Evaluate concept. Next the concepts were evaluated based on the criteria given in Figure 8. In the following we go through each of the criteria and illustrate how they could be evaluated.

Minimize CAPEX. *Cost of equipment.* To evaluate the cost of the different concept, we performed a simplified cost estimate, as it would be too time consuming to do an actual costing of all concepts in the study phase. Based on the experience from previous project, each type of equipment is given a cost factor in terms of a number between 0 and 10. The number of each equipment is identified for all concepts, and a total cost factor is found by multiplying the equipment cost factor with the number off. The cost evaluation is shown in Figure 9, showing that Concept IV would have the lowest equipment cost, while Concept II and III, would be the most expensive.

Equipment	Cost factor	Concept 1 6 slot + 2 x WI	Concept II 2 x 4 slot	Concept III Satellites	Concept IV Multibore XT	Concept V Slim leg
Wellhead	2	7	7	7	7	7
XT	3	7	7	7		7
6 slot maifold with template	6	1				
4 slot maifold with template	4		2			
Overtrawability structure	1	3	2	7	3	
PLET	1	3	5	3	2	3
Inline Tee	2	2	2	7		
UTH	1	1				
SDU	1		1	1	1	
Pig Launcher	2	1		2		
Multibore XT	4				3	
Subsea water processing system	4				1	
Platform	10					1
Total cost factor		**54**	**55**	**64**	**36**	**48**

Figure 9: Evaluation of cost of equipment

Cost of drilling. The first operation on the field is to drill the well. The duration of the operation drives the cost of drilling, due to the high day rate of the drilling vessel. To minimize duration of the drilling operation, it is beneficial to reduce the number of vessel movements. For satellite solutions, each well is drilled separately, giving several rigs moves. This makes concept III the worst concept considering the drilling cost. For the manifolds and the multibore XT, all the wells connected to this will be drilled in one operation, which means that concept I, II and IV needs only one or two rig moves, giving them a neutral score. The best concept for drilling would be concept V as all wells could be drilled from the same location, giving the shortest duration.

Installation of equipment. The cost driver for installation of equipment is the vessel required for the operation. If it is required to do heavy lifting operations it would require a vessel with higher day rates than if the operation could be done from a smaller vessel. Concept I, with the large template and manifold solution will require a large installation vessel, and the cost of installing this is expected to be high. The manifold for concept II is smaller, and will have less need for heavy lifting, and therefore given a neutral score. For concept III, IV, and V the installation can be done from a smaller vessel, giving lower installation cost, which make the better solutions for this criterion.

Installation of pipe lines. For the pipe line, concept I, II, III and V all have separate lines for oil, gas and water and an umbilical for power and chemicals. Concept III is expected to be costlier than the others because of the extensive use of umbilical to distribute power and chemicals to all wells and since the umbilical cross the flow line. Concept V is considered to have less cost of installation, as the distribution is topside. Concept IV has a subsea water processing system, which removes the need for a pipe line for water, which gives lower for installation cost.

Tie-in and connection. Concept I-IV all includes a pipeline end terminations (PLET). What differs in the cost for these layout, is the number of inline tees needed to connect satellite wells to the pipe lines. Therefore, concept I and III consider to be the costliest solution with regards to tie-in. Concept V is assumed to be less expensive as the tie-in and connection will be done topside.

Minimize OPEX. *Cost of operations.* The operating cost in this context covers the cost of operating the field for normal operation, including personal and equipment cost, and the cost of maintenance and repairs. Concept III and IV, is expected to have the lowest cost of operation since it has less equipment which requires maintenance and support. Concept V is assumed to have higher cost of operation, as it includes operating and maintaining the platform.

Cost of intervention operations. Intervention operations are performed to do maintenance of the wells. This is assumed to be easiest for concept V, as it has the wellhead (WH) and XT topside. For concept

IV, doing an intervention operation on one well, would make all the wells connected to same multibore XT out of production during intervention, which would increase the cost of intervention operation. The remaining concept is not reckoned to have any issues with intervention, giving them a neutral score.

Maximize operability. *Flow assurance*. When developing the field, it is important to consider the challenges with flow assurance for the field. For the Donald field with high pressure and potential low start up temperature, the main concern is hydrates formation. To mitigate this there should be continuous methanol injection to avoid formation of hydrates in the flow lines. The field could also have challenges with formation of wax. To mitigate the wax the flow lines should be insulated. All concepts have the same solution with respect to umbilical for chemical injection and possibility for insulating the flow lines. They also have the same possibility for flow metering. Based on this, they all have been given a neutral score for this criterion.

Pigging. Pigging is used to remove wax in the flow lines. Concept III and V is considered the best concept for pigging. Concept III has pig launcher for both the oil and gas production enabling pigging when needed, while Concept V has the flow line terminated topside and could mobilize equipment for pigging when needed. Concept I have also pig launcher, but only for the production line, and is given a neutral score. Concept II and IV is considered the worst concept for pigging. Concept IV have no solution for pigging. Concept II could do pigging using the loop through the template, but this would involve mixing the oil and gas flow, which would introduce flow assurance issues.

Minimize time to first oil. *Phased development***.** To minimize the time to first oil, it is beneficial with a phased development, meaning that some wells could be started before the complete field is developed. For concept III, each of the wells could be drilled completed, and started independent of the other wells, making it the best solution for phased development. Concept V would be the worst concept for this criterion, as the complete platform must be completed before any of the wells could start producing. Concept I, II and IV is all given a neutral score, as they all require several wells to be drilled before development could start, but do not require a complete field development.

Minimize commercial risk **-** *Technology readiness level.* Using new equipment which is not qualified or field proven increases the risk of impact on cost and schedule. Concept I-III is all evaluated as the best solutions for this criterion, as they use only field proven equipment. Concept IV and V is both considered as a worse solution. Concept IV includes a subsea water processing system, which is consider having a low technology readiness level, in addition to the multibore XT which has limited record of use. The slim leg platform in Concept V is in the concept study phase and have a low technology readiness level.

Ensure HSE. HSE, health, safety, and environment, is an important aspect for field development, and this has a high focus in the industry. It is not identified any major HSE issues with any of the proposed concept, and it is expected that all of them could be developed ensuring HSE. Therefore, all the concept is given a neutral score for this criterion.

Minimize footprint. When the field is closed all the equipment should be removed and the impact on the environment should be minimized. It is assumed that all equipment for all the concepts presented can be retrieved after operation, leaving few traces behind. Of these reason, all the concept is a neutral score for this criterion.

Overtrawlability. The concepts with satellites wells, concept I, III and IV, is less appropriate with regards to overtrawlability as the protection structure must be installed separately. For the manifolds the protection structure for overtrawlability can be integrated and installed as part of the manifold, giving the concept with only manifold, concept II, a neutral score. Concept V wellhead and XT topside and minimum need for overtrawlability protection, and is therefore consider as the best concept for this criterion.

Future tie in. Future tie in is included to have the possibility to extend the field with more wells at a later stage of the life of field. All the concepts have solutions for future tie in. For concept I, the manifold has a hub on the end to enable future flow lines to be installed. Concept III, has possibility for future extension by extending the flow lines, or by installing a pipeline end termination (PLET) with inline tee. Concept II has also the possibility for future extension using the PLET with inline tee. All these concepts are considered better for future tie in. Concept IV, have possibility to future extension using PLET with inline tee for gas and oil production, but for the water injection future tie in is dependent on the capacity of the water production system, and is considered as the worst concept for future tie in. Concept V has no restriction for future expansion subsea, but is limited by the space on the topside infrastructure, and is therefore given a neutral evaluation with respect to future tie-in.

Select system solution. Based on the evaluation above, each criterion is given the score S, S+ or S- for each concept, and this is shown in the Pugh Matrix in Figure 10. We have chosen to include weighting of the criteria, translating the low to weight 1, medium to weight 3 and high to weight 5.

Criteria		Weight	Concept 1 6 slot + 2 x WI	Concept II 2 x 4 slot	Concept III Satellites	Concept IV Multibore XT	Concept V Slim leg
Minimize CAPEX	Cost of equipment	5	S	S	-S	+S	S
	Cost of drilling	3	S	S	-S	S	+S
	Cost of installation of equipment	3	-S	S	+S	+S	+S
	Cost of installation of pipelies	3	S	S	-S	+S	+S
	Cost of tie in and connection	1	-S	S	-S	S	+S
Minimize OPEX	Cost of operations	5	S	S	+S	+S	-S
	Cost of intervention operations	1	S	S	S	-S	+S
Maximize operability	Flow assurance	3	S	S	S	S	S
	Pigging	3	S	-S	+S	-S	+S
Time to first oil	Phased development	5	S	S	+S	S	-S
Commercial risk	Technology readness level	3	+S	+S	+S	-S	-S
HSE		5	S	S	S	S	S
Minimize footprint		1	S	S	S	S	S
Owertrawability		1	-S	S	-S	-S	+S
Future tie in		3	+S	+S	+S	-S	S
Weighted sum of +S			6	6	22	16	15
Weighted sum of -S			5	3	13	11	13
Total weighted sum			1	3	9	5	2

Figure 10: Pugh Matrix

From the Pugh matrix, it is found the best concept for the Donald field is concept III with only satellite wells. This solution has some drawbacks related to the cost of equipment, drilling installation of pipelines and tie-in and connection, but scores high on cost of installation of equipment and intervention operations, maximizing operability, technology readiness level and time to first oil.

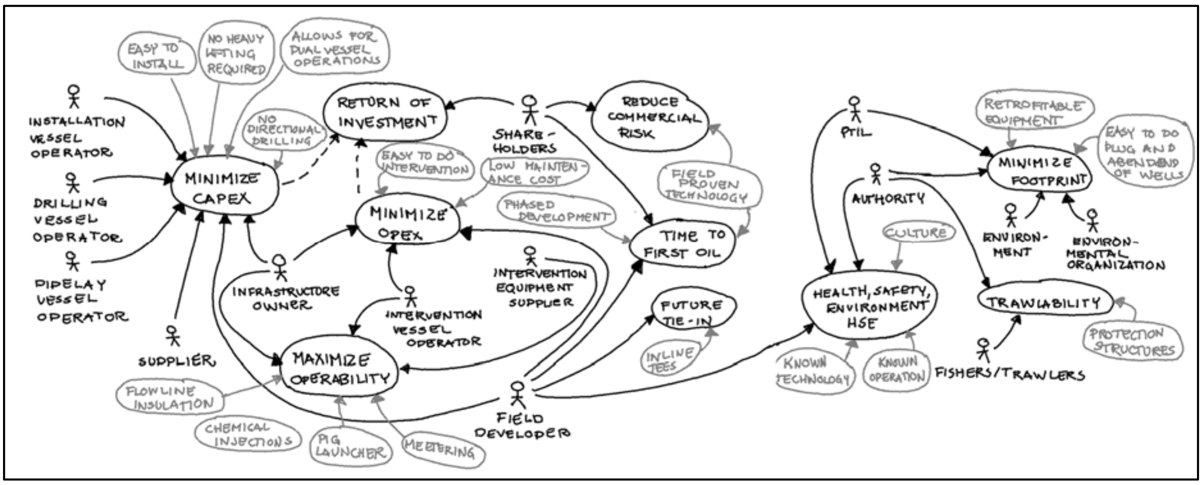

Figure 11: Verification of chosen concept

Verify Concept. Finally, the developed concept should be verified against the stakeholder needs as identified in earlier in the process. This is done by returning to the model of the stakeholders as given in Figure 7. Features of the chosen concept that fulfills a need, is linked to the given need in the model. This simple model for concept verification is shown in Figure 11.

Discussion

Use of system engineering framework. In the research, we have identified that the current processes used for field development do not give proper attention to identification of early phase needs, and is dependent on client having done the identification. The system engineering framework focus on identification of early phase needs, and adapting the initial steps from this framework to the company process, will improve the quality of the study and reduce the number of late design changes.

Use of unformal model. In the new field development process, we have suggested to include graphical models to enable communications in the study phase and to ensure proper documentation for later phases. We have suggested to use quite simple models, to introduce the concept of modelling to the early phase work. The use of model makes is easier for the reader to see origin of the needs and requirements and understand the evaluations and decisions done in the study phase. Also, the models leave less room for misunderstanding than the traditional text based documents do. Using the models, it is also easier to understand the impact if the stakeholder needs and requirements changes from study to tender, and what needs to be updated in the evaluations and decisions based on the changes.

Towards formal model. Model based system engineering is emerging in several industries, and the subsea industry is starting to adapt more formal models and transforming towards a model based system engineering method. In the study phase, the work is rapid, and there is little will to introduce formal models and methods. By using the unformal models in the study phase, we believe we set up a foundation for using formal models when the project moves to the tender and execution phases.

Applicability of the result. The combined process is made on a generic level; hence it should be possible to adapt the process for all early phase work. The case study is performed on a superficial level, to give the reader an indication of the consideration involved in a field development study, and to illustrate the use of models. In an actual study, there is much more technical work and analysis involved in evaluating the field layouts, such as flow assurance analysis and hydraulic and electrical stimulation. Also, the case study is only showing technical evaluations, whilst in a real case there are other factors influencing the evaluation, for instance company strategy, commercial or other business-related issues. However, the format of the model is made such as it can be expended to include both additional technical complexity and other factors influencing the decisions. In fact, it is the authors opinion, that the models are even more applicable and important as complexity of the case study increases.

Credibility of data and limitations of the research. In our research, we have used the experience and knowledge of senior resources in the company in addition to analysis of a selection of study report input to our research. The input from the seniors are based on their experience and gut feeling, and may not reflect the absolute truth. However, the findings from our internal research matches the concerns raised by the OG21 reports (OG21, 2015a, 2015b), and it is believed that the data gives a good picture of the state of the industry.

Application in company. The improved process is not applied fully in the company, but some elements from the method has been applied. The company is currently using the Pugh matrix in their studies, and the use of the weighted matrix is increasing. It also seen that use of graphical models and to some extent the concept of operations is used to ease the communication in project and with client. In the later study it is also seen an increased focus on the requirement management, and a significant effort is done to document the rationale behind the decisions.

Further work. The subsea industry is changing, and several articles are pointing to model based system engineering as a solution for the future of the industry. However, it is also seen that the industry is reductant to introduce formal modelling methods, as they are considered rigid and time consuming. In this article, we have shown a simple approach of modeling, to introduce the concept to the early phase work. More work is needed to find the appropriate level of modelling in the different life cycle phases for the subsea system.

Conclusion

The subsea industry is changing and the company processes and methods must be adjusted accordingly. Research within the company shows that the process currently used for field development is working adequately for study where the client has a strong opinion of the system solution they desire. However, the concept studies are changing, and clients in a higher degree expect the company to develop a concept from scratch. It is also a trend that the concepts are integrated projects, which means that the concept for subsea and surf are developed together.

The process currently used for concept study is dependent of client giving a complete set of needs. We have proposed a new process, including steps from the System Engineering Framework, to be able to identify all relevant stakeholder and stakeholder needs in the early phase. We have proposed to increase the use of models in the process, to better communicate the evaluations and decisions in the study phase. This improves the documentation of the study for the later project phases.

Acknowledgement

The case study was originally done as a student work by the first author, and the field layouts were developed as part of a group work.

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Biography

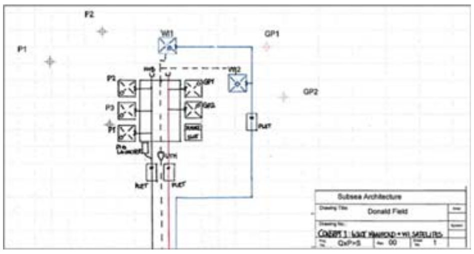
Siv Engen is an Industrial PhD candidate at University College of Southeast Norway. Siv holds a Master of Technology in Engineering Science and ICT, with specialization in Marine Constructions from NTNU, Trondheim. She has 10 years of experience from major subsea supplier, and is doing her PhD research within the company.

Kristin Falk is employed as Associate Professor at University College of Southeast Norway, where she is responsible for the Subsea track and fronting research on systems engineering. Kristin holds a PhD in Petroleum Production and a Master in Industrial Mathematics, both from NTNU. She has worked with research, development and management in the oil and gas industry for 20 years, both with major subsea suppliers and with small start-ups.

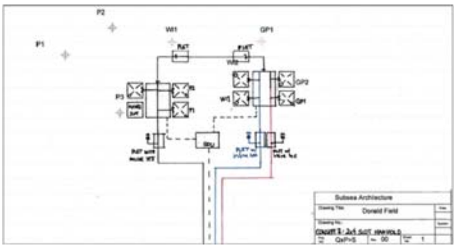
Appendix

The layout discussed in this paper is shown in Table 1 together with a description of each concept. A brief description of all equipment is given in Table 2.

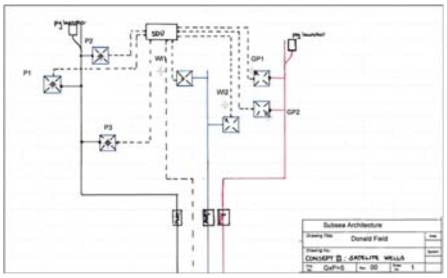
Table 1: Concepts for field development



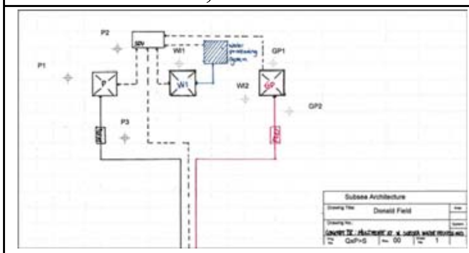
Concept I: 6 slots manifold + water injection satellites. Concept I is based on a 6-slot manifold combined with satellite wells for water injection, as shown in the layout. The manifold has three oil productions XT and two gas production XT, in addition to one open slot for future extension. The manifold has one flow line for oil and one for gas. The umbilical for power and chemicals is connected to the manifold which distributes power to the water injections trees in the satellite wells. The umbilical is terminated using an umbilical termination head. The water injection trees are placed as satellite wells and connected to a separate flow line for water using inline tees. For this concept the water injection wells are placed on top of the drill center, using only horizontal drilling, while the production and gas wells is in the center of the field and should be drilled using directional drilling.



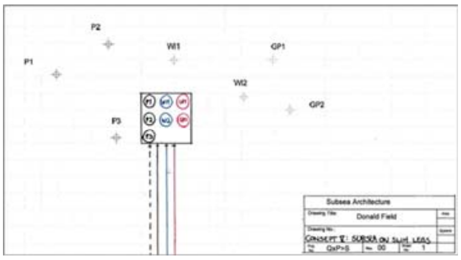
Concept II: 2 x 4 slot manifolds. Concept II is a based on two smaller manifolds, each with 4 slots as shown in the layout. One manifold is for the water injection and the gas production trees, while the other is for the production trees with a slot for future extension. There are separate flow lines for gas and water going into one of the manifolds and a separate flow line for the oil production to the other manifold. Between the manifolds there is a flow line to create a loop to enable pigging. This line should be closed by valves avoid mixing of gas and oil in the flow lines. The umbilical is for this layout ended in a Subsea Distribution Unit, SDU, which distributes power and chemicals to the two manifolds. For this concept the manifold is placed in the center of the field and the wells will be drilled using directional drilling.



Concept III: Satellite wells. Concept III is based on satellite wells, with the trees placed above the drill center for each well as illustrated in the layout. The layout has separate flow lines for oil, gas and water and the wells are connected to the flow lines using inline tees. The umbilical is terminated in a subsea distribution unit which provides the power and chemicals to each of the XT. For this layout, all wells a place directly above the drill center, which means there is no need for directional drilling.



Concept IV: Multi-bore XT with subsea water processing system. Concept IV is a solution with three multi-bores XT, one for oil production, one for gas production and one for water injection as shown in the layout. A multi-bore XT can take the flow from several wells into one XT. There are separate lines for oil and gas going into the corresponding XT. There is no line for water injection, instead it is included a water processing system, which provides water to the water injection trees. The umbilical is terminated in a subsea distribution unit, which distribute power and chemicals to the water production system and the multi-bore XTs. For this concept the well will be drilled using directional drilling.



Concept V: Subsea on slim legs. Concept V is a solution where the XT and WH is installed topside rather than subsea. The field layout for the concept is shown to the left. It is chosen "subsea slim legs" rather than "subsea on a stick" to have a robust solution to be able to operate at the given water depth weather condition in the Norwegian Sea. On the platform, there will be a wellhead and a XT for each well. The platform has 3 flow lines, one for oil, one for gas and one for water. In addition, it has an umbilical for chemicals and power. The wells should be drilled using directional drilling.

Table 2: Description of equipment

Wellhead (WH)	The wellhead is installed at top of the well, and its purpose is to provide a pressure-containing interface to the well.
X-mas tree (XT)	The XT is installed at top of the WH, and its purpose is to be a pressure barrier and to control the flow of the valve during operation. **Multibore XT** is a XT with multiple bores, enabling several wells to be integrated in one XT.
Manifold and template	The purpose of the manifold is to merge the flow from all wells into the flow line for export back to infrastructure. The manifolds are installed with a template, which is a foundation to support the manifold. The 6 slots manifold is an "on-template manifold system", where the manifold is installed with a template and the trees are connected directly to the manifold. The 4 slots manifold is a smaller manifold, which provides the same functionality as the 6 slots manifold, but due to its reduced sizes it simplifies installation.
PLET	PLET, pipeline end termination, is installed subsea, and the purpose is to provide a stable end for connection of the flow line.
Inline Tee	The inline makes it possible to tie in a branch flow line for connecting satellite wells or for future expansion of field.
UTH	UTH, umbilical termination head, is installed subsea to provide a method for termination of the umbilical before connecting to the manifold.
SDU	SDU, subsea distribution unit, provided termination of the umbilical, but in addition it acts as a distribution unit, providing power and chemicals to all XT.
Pig launcher	Pig launcher is installed subsea to enable pigging of the flow lines.
Water processing	The purpose of the water processing system is to process seawater to fresh water, to be used for water injection.

Article 2

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Architectural reasoning in the conceptual phase - a case study in the oil and gas industry

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***Abstract* — This paper evaluates the use of architectural reasoning to explore the problem space in a system development project in the oil and gas industry. The suppliers in this industry have traditionally been tailor-making their systems for each delivery project. To improve the systems offering across the client and project portfolio, the suppliers must put more effort in the conceptual phase to explore the design space. Architectural reasoning is the process of transferring problem and solution know-how into a new systems architecture. In this paper we review literature on architectural reasoning in the conceptual phase, and on application in the oil and gas industry. To evaluate the use of architectural reasoning in the industry, we perform a case study in a subsea supplier company. From the case study, we are identifying a work-flow for architectural reasoning, utilizing the market needs, design, and domain knowledge to evolve the system. Evaluating the tools and working methods, we find that working in a multi-disciplinary team is key to support the reasoning process. We find that the team is utilizing the design and domain knowledge to improve the system architecture. However, the team lacks methods to make this knowledge explicit and to quantify the issues they are identifying.**

Keywords—architectural reasoning, conceptual design, oil and gas industry, case study

I. Introduction

Oil and gas suppliers are constantly working to improve their system offerings, by reducing the installation cost and schedule. Traditionally in this industry, the clients have been giving extensive and detailed requirements specifications. The specifications are often of poor quality and is a mix of requirements and prescribed solutions [1]. Reports from the industry show that the extensive requirements increase the cost as it requires customized system solutions, and do not enable suppliers to optimize their system offering across the client portfolio [2]. Currently, we see a shift of the industry, and the clients are more open to the supplier being a part of the development of the system solutions [3], "in press" [4].

With this shift, it opens for the supplier companies to rationalize their system solutions across their client and project portfolio. This requires supplier companies to have processes for supporting the conceptual phase to explore the design space. Systems architecting can support this exploration. Reference [5] describes systems architecting as a joint exploration of requirements and designs.

Architectural reasoning is the process of developing the system architecture. In this paper, we evaluate how architectural reasoning can support a supplier company in developing system solutions across their portfolio. First, we present a review of the existing knowledge of architectural reasoning and its importance in the conceptual design phase. We also look to the literature of implementation of systems architecture in the oil and gas industry. Next, we present a case study from a supplier company in the oil and gas industry. In this case study, we observe the use of architectural reasoning in an ongoing development project. We are describing the reasoning process the team are using and compare it to the existing literature. Finally, we describe the tools and working methods the team is using to support their reasoning and evaluate how the team perceive these tools.

II. Research Methodology

This paper contains two parts, a literature review and case study. The literature review is aiming to provide the understanding of architectural reasoning and its role in the conceptual phase. The second part of the paper presents a case study from the oil and gas industry. The case study is applying the research method industry-as-laboratory [6]. The first author is a part of a development team in the company and collecting data based on observations of the daily work. Further, we were using a survey to evaluate how the team was perceiving the methods and tools they were using. We were distributing the survey to all team members and got response from all of them.

In the survey we used a five-point Likert scale [7], with response alternatives *Strongly disagree (1)/ disagree (2)/ neither agree or disagree (3)/ agree (4) / strongly agree (5*). For all questions we gave the respondents the possibility to answer *not applicable* if they had not been involved or exposed to the given tool or method. The survey results presented in the paper are not including the *not applicable* responses.

To compare the methods relative to each other, we analyze the tendency using the median [8]. To evaluate the overall supportiveness of the methods, we use the Net Promotor Score (NPS) [9], considering strongly agree as a promoter, agree as neutral and neither agree or disagree, disagree, and strongly disagree as detractors.

III. Background

A. Systems architecture and architectural reasoning.

There is no unified definition of systems architecture, and the system engineering community is considering systems architecting more as an art [10]. ISO/IEC/IEEE defines systems architecting as *a process of conceiving, defining, expressing, documenting, communicating, certifying proper implementation of, maintaining and improving an architecture throughout a system's life cycle*.

Systems architecture can support the development project in exploring the needs and design of a system [10]. The importance of systems architecture is to enable a way to understand complex systems, to design and manage them and to provide long-term rationality of decisions made early in the project [11].

To support development of systems architecture, there exist several architectural frameworks. Architectural frameworks intend to provide a standard approach to architecture [12]. Reference [5] and [12] presents reviews of exiting architectural frameworks. In [12] the authors focus on the differences in the frameworks. They conclude that the one should adapt architectural framework to the goal and context.

Architectural reasoning is the process of developing the systems architecture. Reference [13] presents a schematic model for architectural reasoning, describing it as recursive process driven by system requirements, available domain knowledge and available design knowledge. In [14] the author gives a thorough introduction to architectural reasoning and what it means in an industrial setting. This work is based on the CAFCR framework [15]. The purpose of this framework is to support systems architecture.

The CAFCR framework decomposes the architecture into five views, *customer, application, functional, conceptual* and *realization*. Within each of the different views, the author suggests different sub-methods that can support developing the systems architecture. Among these methods is the key driver method. A key driver is defining the most important objectives of the customer, that is, *what does the customer want?* [16]. Using the key driver, the system architect can build a key driver graph, which provides a method to connect the customer key drivers to the system requirements. Another framework using key drives, is the FunKey framework [17]. In this method the author proposes to relate the function of the system to the key drivers and requirements by using a matrix to couple them.

B. Conceptual design phase.

The early phase of system design is the conceptual phase, in which one explores the business opportunities and needs, and develops high-level concepts [18]. The definition of the systems architecture occurs in the conceptual phase and is one of the key activities in this phase [19]. As new products are becoming more complex and multi-disciplinary, with shorter development cycles the role of the systems architecture in the conceptual phase is becoming more important [20].

In the early phase, it is important to make the right design decisions, as poor design choices could lead to late design changes, carrying the risk of cost overruns and schedule delays. In [21] the authors are listing some of the main reasons of poor design choices. This includes the lack of a common language and background for multiple engineering disciplines and that design choices based are on experience and intuition rather than quantitative arguments. Other work discussing challenges of multi-disciplinary development in the conceptual phase, also identify communication and decision making as critical issues [22] [23].

To improve the final system design, the developers need to consider and explore the problem domain in the conceptual phase [19]. One process to support this is the Boderc design methodology for high-tech systems [21]. The purpose of this framework is to support efficient evaluation of design choices over multiple disciplines. They split the method in three high-level steps. First step is *preparation of design*, identifying realization aspects of concern, key drivers, and requirements, and making core domain explicit. Next step is *select critical design aspects*, identifying tensions and conflicts and quantifying them. Last step is *evaluation of design aspects,* using models and measurements.

Reference [14] gives a similar flow from problem to solution, consisting of 4 steps, *problem understanding, analysis, decision,* and *monitor, verify and validate*. The first step is to create an understanding of the problem. To do this, one needs to explore both the problem and solution space. In the analysis step one should explore multiple propositions through systematic analyses. The next step is to make a decision by reviewing the analysis and to document and communicate this decision. Finally, the team should verify and validate the solution by measurements and testing.

C. Systems architecting in oil and gas industry

The oil and gas industry can have great benefit of systems engineering methods and techniques, but they must adopt it their own setting and needs [24]. Since early 2000 the cost level in the industry has been rapidly increasing. With the drop in the oil price it became challenging to develop profitable fields [25]. Tranøy et al. analyzed cost overruns in a supplier company in the oil and gas industry and found that the company spend sufficient effort in systems engineering [26]. They also concluded that the major reason for cost overruns was the poor identification of operational needs during early phase. Engen et al. evaluated the use of system engineering in the front-end engineering and design phase [3]. They identified shortcomings in the understanding of the needs in early phases and in documenting design decisions. To improve the system engineering process, they proposed to use informal models to document decisions. Solli investigated the use illustrative ConOps and found that this can improve the mutual understanding among the stakeholders and identify concern in early phase [27].

Another tool that can be effective and improve the system offering in the subsea industry is A3 Architectural Overviews (A3AO) [24]. Borches introduced the A3AO to support sharing of architectural knowledge [28]. In [29] the authors show the use of A3AO in combination with conceptual modelling for a workover system. They found that the A3AO connects the technical system to the business interest, which facilitate the discussion with the stakeholders. Reference [30] gives another example of implementation of A3AO. Here, the authors conclude that A3AO is a well-suited tool to improve communication and collaboration within industry. At the same time, they identify challenges related to implementing this in the industry. They find part of the organization reluctant to implementing and using A3AO, mainly due to the time spend on making the reports and the lack of integration with existing company tools. Reference

[31] support these finding, stating that the subsea industry often meets introduction of more formal methods by skepticism, and that they are perceiving the methods as time-consuming and not applicable.

IV. Case Study - Architectural Reasioning in Oil and Gas Industry

A. Introduction

In this case study, we focus on how architectural reasoning supports a multi-disciplinary team in a development project. The aim is to evaluate the use of architectural reasoning in an industrial setting. We are observing the daily work in a development project and the tools and methods supporting the team in their work. From our observations we identify a work flow for understanding the problem. To evaluate how the tools and working methods are supporting the architecting process, we did a survey among the team members. In the following section we present the case study and our findings.

B. The case

The case we are following, is a development project in a global supplier of equipment to the oil and gas industry. The purpose of the project is to evolve the system design, to reduce installed cost and schedule. The supplier company put together the development team by allocating engineers from different product disciplines and project groups. We call them the core team, with 14 members including the first author. Most of the members of the core team are co-located in an open office area, enabling daily discussions and knowledge sharing. In addition, the team has support from other business functions, such as manufacturing, supply, and costing. The team is following a lean product development process [32], but without any clear process for how to do systems architecting.

C. A work flow for initial phases of architectural reasoning in supplier company

When the team started their work, they were spending most of their time on understanding the problem. We observed that the engineers easily got down to the details of the solutions and were eager to "get going" with the design and engineering. This is similar to what the authors in [33], have seen in other development projects. They conclude that it is a challenge that *many engineers think in solution.*

As the team was progressing they understood that they should explore the problem and solution space more broadly. To do this the team was exploring the design and domain knowledge in the company to understand the issues and tensions of the existing system. In addition, they explored the market prospect to understand the needs for a new system solution. This data collection was supporting the team in understanding the problem. Next the team focused on selecting what they should prioritize to improve, to meet the overall target development project. To do this the team quantified the issues and needs they had identified during the problem understanding, using simple models. For the selected system issues, the team started to explore the design solution space. The phase of evaluating the design space is not within the scope of this paper.

In Fig. 1 we summarize the work flow the development team is using. It starts with a problem statement from the stakeholders. First step is *understanding the problem to solve,* where the team explores the problem and solution space to gain understanding of the problem.

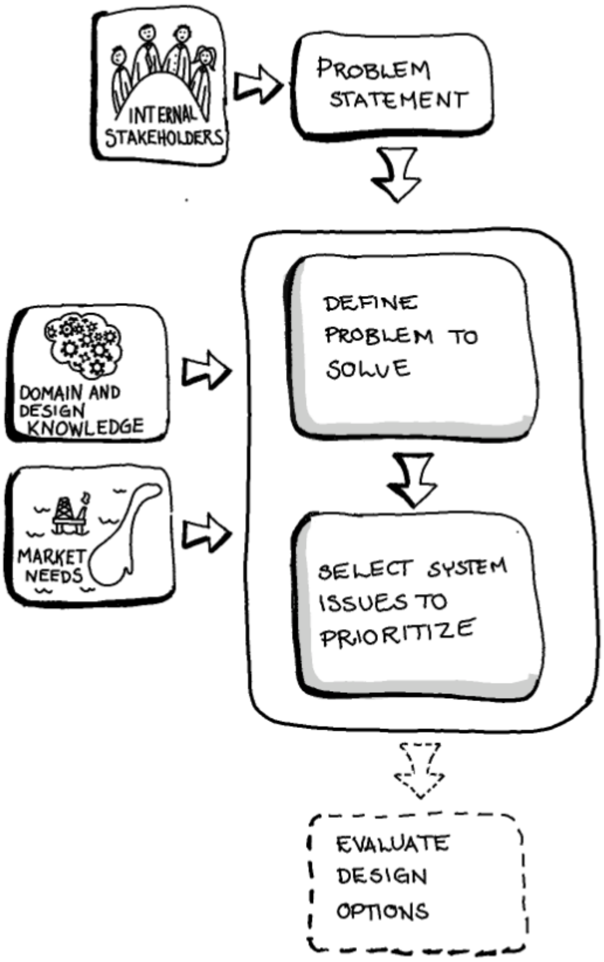

Fig. 1. The flow from stakeholder problem statement to selection of system issues to solve

This first step is comparable to what is the Boderc Method call *preparation phase* [21] and what Muller refers to as the *problem understanding* [14]. Next step is *select system issues to prioritize,* where the team analyzes the issues collected in the understanding phase and selects what is most important to solve the overall problem. This step has similarities to Boderc *select critical design aspects* and Mullers *analyze* step.

The left-hand side of Fig. 1 is showing the input data to the process. The team is utilizing the domain and design knowledge as well as the market needs to support their reasoning. This is equivalent to the schematic model describing architectural reasoning.

D. Methods and tools supporting the architectural reasoning in the supplier company

In the work with understanding the problem and selecting system issues to solve, the team used several tools and working methods. As the project follows the lean product development process, they are utilizing the **A3 problem-solving tool** [34]. The A3 report follows 6 steps to describe and understand the problem. The team is mainly using the left-hand side of the tool, which contains problem statement, background, current condition, and analysis. In the current condition and analysis, the team utilized simple models and problem-analysis tools to show the cause-and-effect relationship [34].

To gather data the team had a structured **workshop identifying the issues with the system today**. Firstly, they reviewed the functionality of the system before they identified the known issues with the major sub-systems and products. From this the team was able to identify the most important system issue to solve across the products and sub-systems. The outcome of this workshop was a power point slide illustrating the system issues identified in the workshop. To gather experience of how the market perceives the current system offering, the team had several **lessons learned workshops** bringing in key resources from previous development projects and tenders recently executed. These workshops were unstructured conversations, with the purpose of sharing knowledge. No one was documenting these workshops.

To extract the customer needs, the team performed a **market assessment**. Members from the team performed semi-structured interviews with the front-end managers and the system engineers in all ongoing field studies. The outcome from these interviews were a summary map showing all market prospects and data sheets visualizing the key technical data for each of the fields.

As part of the market assessment, the first author introduced **key drivers** to the development team. In all interviews the team was asking the system engineers to identify the top three key drivers for their study. Based on this and the information from the lessons learned workshop, we extracted the top three key drivers for each of the customers. In addition, we were identifying the **customer attitude,** weather they are open for change and willing to accept innovative solutions from the suppliers, or if they are more reluctant to change.

Using a survey, we asked the core team to evaluate how these tools and working methods have support the understanding of the problem and the selection the system issue to prioritize. We also asked the team to evaluate how working as a multi-disciplinary team has supported the reasoning process. Fig. 2 - Fig. 4 are presenting the result from the survey.

From the survey we see that the team is identifying working as a multi-disciplinary team as most supporting in both understanding the problem and selecting system issues. Research has shown that lack of multi-disciplinary knowledge is one of the key issues in conceptual phase. In [23] the authors highlight as an issue that the engineering education discipline oriented and that the engineers do not have sufficient knowledge of other disciplines. We observed that co-location of the multi-disciplinary team contributed to a knowledge sharing across disciplines and supported their understanding of the system. The survey result is supporting this observation, see Fig. 4.

The team is also finding the lessons learned workshops and the workshop identifying issues to be supportive in understanding the problem. This also follows the reasoning that sharing knowledge across domains is key to explore the problem domain. In selecting the system issues to focus on, the workshops get a close to neutral NPS score, which is natural as they are based on qualitative data.

The team is perceiving the market assessment and the key drivers as supportive in understanding the problem. However, looking at the NPS score, these get a close to neutral score. In selecting system issues the market

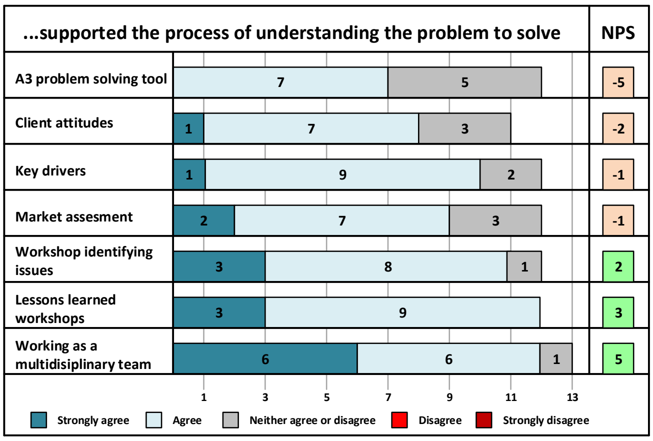

Fig. 1. Survey result - tools and techniques to support the understanding of the problem

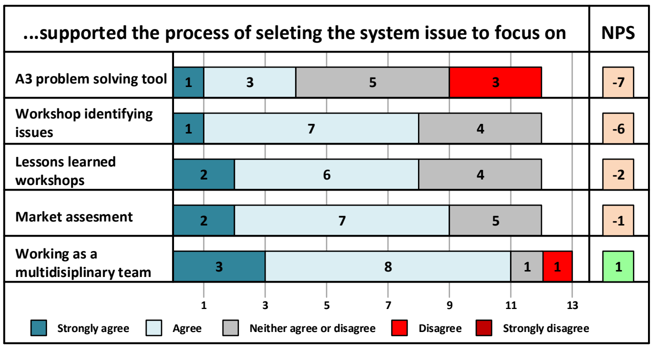

Figure 2: Survey result - tools and techniques to support the selection of system issue to prioritize

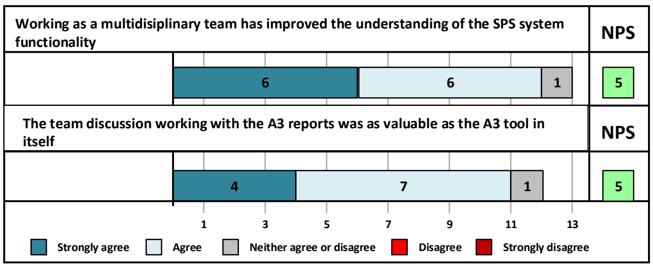

Figure 3: Survey result - general

assessment is among the most supportive, but again it has a close to neutral NPS score. In the daily work, we observed that the team was using the market assessment and the key drivers to communicate outside the team, to explain the reasoning and the decision made in the project to the stakeholders.

The tool getting the lowest score in both phases is the A3 problem-solving tool. This tool gets a poor NPS score, especially for supporting the selection of the system issues. Observations in the team showed that the team struggled to fit their problems into the format of the A3 problem solving tool. However, we observed that the work with the A3 triggered important discussion in the team that was valuable for the problem understanding. The survey result in Fig. 4 is supporting this observation, showing that most of the team members found the discussions when working with the A3 more valuable than the tool itself.

V. Discussion and further work

Architectural reasoning is the capability of developing a systems architecture and exploring and relating the needs and design of a system. Former research reveals the importance of doing architectural reasoning in the conceptual design phase to capture the system needs. The literature identifies several challenges leading to poor design decisions in the early phase. One of the key issue identified are the challenges with communication in multi-disciplinary teams.

The case study showed that the team perceives working multi-disciplinary as a key factor to understand the problem and select system issues. Sharing knowledge between the team members and with other resources in the company, is important to explore the problem domain. The use of informal workshops and discussions support communication and enables the team to understand different perspectives and quickly clarify misunderstandings. The challenge with this communication form, is that the team is sharing the knowledge orally without documenting it properly. As a result, knowledge gained in the discussions is not made explicit to those not involved. This limits the knowledge transfer.

We observed that the team followed a generic workflow for architectural reasoning, similar to those found in literature. But the team did not apply the associated tools and working methods for architectural reasoning. Instead, they choose tools and techniques based on their experiences. The survey showed that none of the tools is good enough to support the team in their reasoning process. The results from the survey and observations in the team shows that the team struggles to quantify the design issues and tension, to make the design decisions. This is coherent with challenges identified in literature, [21] [22] [23].

Systems requirement, design and domain knowledge drive the architectural reasoning process. In the case study we find that working in multi-disciplinary teams are effective to support the reasoning process. However, there is a lack of tools to effectively capture and communicate the architectural knowledge. A3AO, [28], is a tool to support knowledge sharing and it is shown that there are great benefits of using the tool in the oil and gas industry, [29] [30]. Still there are challenges with the use of A3AO, hindering a broader implementation of the tool in the industry, [30]. The case study also shows that it is a challenge to quantify issues and tension in current design, to ensure the development focus on the most important systems issues. The Boderc framework, [21], suggests the use of models and simulations to support this quantification. Reference [29] shows a case where they have implemented conceptual modeling in industry to quantify design issues and extract operational needs. Even though this case shows promising results, there is limited use of such models in the industry. Further work should investigate the use of conceptual models to support quantification of issues and sharing of knowledge in the industry, with the purpose to understand the success factors for implementing conceptual models in the industry.

From the literature review we identified key drivers, [16], as a method suitable for the development project. We introduced this method to the team. In the daily work we observed that the team members used the key drivers, and that it was supporting the communication with stakeholder. Yet in the survey the key drivers got a neutral NPS score. Further work should continue the evaluation of key drivers as a tool in the early phase work and evaluate how to evolve the method to fit the needs of the subsea industry.

VI. Conclusion

The oil and gas industry are immature in implementation of system engineering. This industry often perceives system engineering tools and processes as too formal and time consuming. Research within the oil and gas domain shows great benefits of implementing system engineering, [24]. At the same time, it shows that the industry must adopt the methods and techniques their setting and needs.

Since the downturn in the oil and gas industry in 2010, it has been an increasing focus on developing low-cost solution, "in press" [35]. This have led to a shift in the industry, and the suppliers is getting more involved in the conceptual phase of the development. To accommodate this, the suppliers needs to have processes for supporting the conceptual design phase to explore the design and problem space.

This paper provides a case study of how a major subsea supplier applies architectural reasoning in the early phase of a development project. From the case study, we identify two main challenges in the early phase work. These are sharing architectural knowledge, and quantifying tensions and issues. These observations coincide with the challenges identified in the literature, and other work points at conceptual modeling as a technique to meet these challenges. Future research should explore how the learnings from other industries could be adopted to be successfully implemented in the oil and gas industry.

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Article 3

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systems

Article

The Need for Systems Awareness to Support Early-Phase Decision-Making—A Study from the Norwegian Energy Industry

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Abstract: In this paper, we explore the need to improve systems awareness to support early-phase decision-making. This research uses the Norwegian energy industry as context. This industry deals with highly complex engineering systems that shall operate remotely for 25+ years. Through an in-depth study in a systems supplier company, we find that engineers are not sufficiently aware of the systems operational context and do not focus on the context in the early phase. We identified the lack of a holistic mindset and the challenge of balancing internal strategy and customers' needs as the prevalent barriers. To support the concept evaluation, the subsea system suppliers need to raise systems awareness in the early phase. The study identifies four aspects that are important to consider when developing and implementing approaches to improve systems awareness in the early phase.

Keywords: systems awareness; systems architecting; decision-making; key drivers; systems context; systems of systems; subsea field development; energy industry

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1. Introduction

An oil and gas field development is a complex system development with many constituent systems and actors. In the early phases of an oil and gas field development, the subsea systems suppliers develop and propose system concepts for the field on behalf of the oil companies. Based on these concepts, the suppliers commit to cost and schedule. Making the correct design decisions in this phase is key to making the project viable [1]. As the system design matures, the cost of changes becomes increasingly expensive [2].

Systems architecture can support exploring the needs and design of a system [3]. The importance of systems architecture is to enable a way to understand complex systems, to design and manage them, and to provide long-term rationality of decisions made early in the project [4]. In our paper, we follow Maier's definition [5], considering architecture as a set of decisions about the system, making architecting a decision-making process. The decisions made in the early phase of system development are what decide most of the system's value, cost, and risk.

A major reason for the cost overruns in the oil and gas industry is the poor identification of the operational needs in the early phase [6]. In such industries, where the end-user is not directly involved in the development, operational requirements and life cycle considerations often have lower priority than minimizing initial capital expenditures. However, understanding the interactions of all products, systems, and services is key to developing systems that operate as intended [7]. Architecting and designing good constituent systems requires awareness of the context in which they operate and understanding of the system's role in a larger capability [8]. In [9], Muller reflects on the stakeholder's awareness of the encompassing Systems of Systems (SoS) based on experience from active participation, consulting, and educating in the industry. Through several cases from multiple domains, he finds poor exploration and understanding of the encompassing system, resulting in problems during integration, commissioning, or deployment of the system in the broader context.

In this paper, we conduct an in-depth study in the context of the oil and gas industry, evaluating the engineers' awareness of the SoS and the operating context of their system. The company of research is a major supplier of systems and services to the oil and gas industry. Globally, the company has more than 20,000 employees. We have executed our research within the Norwegian branch of the organization, with ~2000 employees. Through our study, we aim to answer the following research questions:

RQ1: How aware are subsystem and system engineers of the encompassing system and the operational context of their system during the early phase?

RQ2: What are the barriers to exploring and understanding the system and operational context in the early phase?

RQ3: Which aspects are important to consider when developing and implementing approaches to improve systems awareness in the early phase in the subsea industry?

The context for this paper is the early phase of projects in the subsea domain. The INCOSE Systems Engineering Handbook [10] provides an overview of the generic life cycle stages, as shown in Figure 1. Our work is within the exploratory phase. The main activities in this phase include defining the problem space, characterizing the solution space, identifying stakeholder needs, and exploring feasible concepts.

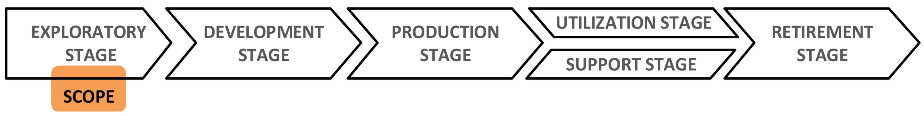

Figure 1. Relation of our work in the INCOSE life cycle stages.

The following section gives a brief introduction to the Norwegian energy industry, followed by a literature review on early-phase decision-making. Next, we present the research method used in this paper. In Section 5, we offer the results from the study, and in Section 6 we discuss the findings from the research, answer the research questions, and present further research. Finally, we give a conclusion in Section 7.

2. Background

2.1. The Norwegian Oil and Gas Industry

We have conducted our research within the context of the Norwegian energy industry. Since the first oil and gas field development at the Norwegian Continental Shelf in the mid-1970s, the petroleum industry has been an essential contributor to Norwegian wealth. From 2000–2014, the industry had its golden age, and the incomes from the sector contributed to 12% of the country's Gross Domestic Product [11]. In this period, operators developed a high number of new fields at the Norwegian Continental Shelf. The focus was on delivering the subsea systems with short lead times. The cost level increased rapidly in this period, and the cost increase was significant compared to the activity increase [12]. In 2014, the oil price dropped significantly, and the oil and gas industry globally went through a downturn. Following this downturn, the oil and gas industry has undertaken several changes to cope with the challenges. We highlight three shifts that have significantly changed the industry:

- From Capital Expenditures to Total Cost of Ownership. Traditionally, the industry's focus has been on Capital Expenditures (CAPEX), that is, the cost of producing the system and commissioning it for operation. However, since the downturn, the focus has shifted towards the Total Cost of Ownership (TCO), including the Operational Expenditures (OPEX), which is the cost of operating the system through its life cycle.
- New business models and joint ventures. The subsea systems consist of the subsea production systems (SPS) and subsea umbilicals, risers, and flowlines (SURF). Traditionally, there has been a split between the contracts on SPS and SURF. Following the

downturn, the suppliers have formed alliances and joint ventures to concentrate the market and reduce competition [13].

- Energy transition. The oil and gas industry plays an integral part in meeting the goals of reducing greenhouse gas emissions. All actors in the industry face increasing demands to clarify the implications of energy transitions for their operations and business models and explain the contributions they can make to achieving the goals of the Paris Agreement [14].

The change from CAPEX to TCO increases the focus of the operational scenarios in the early phase. Previously, the operational needs have been given little consideration in the early phase [15], leading to costly late design changes [6]. The new business models and joint ventures also increase focus on the operational scenarios, as the suppliers take responsibility for a larger part of the scope. Consequently, the suppliers are responsible for more of the systems' interfaces and interactions. To succeed with the new contracts, the suppliers are dependent on taking a holistic approach and utilize the system knowledge across legacy organizations [16]. In addition to these changes, the industry is highly affected by the energy transition. This transition requires the suppliers to measure and contribute to reducing the overall CO2 footprint of the field development. These changes in the industry require that the system suppliers have a higher awareness of the system context and the operational context of their system.

2.2. Systems Engineering in the Oil and Gas Industry

The oil and gas industry is immature in implementing systems engineering compared to other industries [17]. One of the main reasons for immaturity is that it has not been necessary. The focus in the industry has been on delivering high volume as fast as possible, without the concern of the high cost following inefficient development. However, after the downturn, the industry is looking towards systems engineering to improve their offering [18]. Even though subsea companies are increasingly applying systems engineering methods and recognizing their value, implementing new work processes in mature organizations is challenging [19,20]. Muller et al. state that the industry can benefit from implementing systems engineering methods and techniques, but it needs to adapt them to their specific circumstances and needs [21].

2.3. Clarification of Terms

In this paper, the system is the subsea production system the company delivers to the field development. The system consists of subsystems. Each subsystem is typically treated as a work package in the project execution. The subsystems consist of components. Figure 2a shows the definition of and relation between the components, subsystems, and the system.

Figure 2b illustrates the systems of systems, the field development. The system in operation refers to the company's system, the system, as a part of the whole field development. The other systems in operation refer to the other systems that are part of the field development, such as vessels and rigs, the topside facility, and other subsea systems installed at the field. Note that we have illustrated the company's system with a subsea system known as an on-template system in the figure. An on-template system typically operates 4–6 wells. In a field development, the subsea suppliers typically deliver 2–6 on-template systems to operate more than 30 wells in total. Interested readers can refer to Leffler et al. [22] for more information on the oil and gas field development.

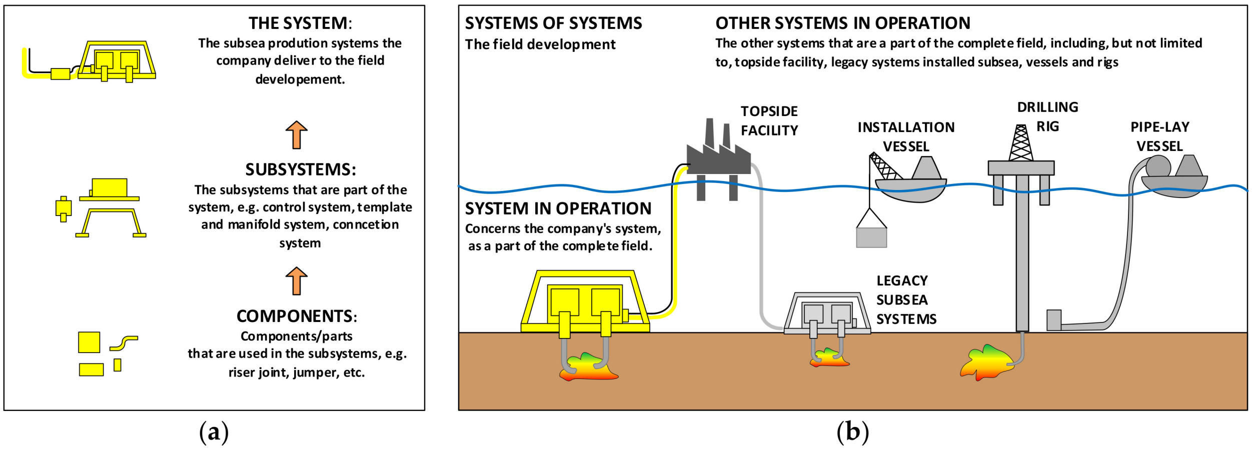

Figure 2. (**a**) Relation and definition of the system, subsystems, and products. (**b**) Relation and definition of the super system, the system in operation, and the other system in operation.

3. Literature

3.1. Concept Evaluation in Early Phase of Oil and Gas Field Development

Decision analysis is important in the early phase of the field development to optimize the production profile and improve project performance [23]. The literature on concept evaluation in the early phase of field development shows extensive use of detailed simulations to support decision-making. An example is given by Angert et al., presenting the use of a company-developed operation evaluation technology to run a large amount of simulations to optimize field layout [24]. Bratvold and Begg review the common practice of decision-making in the oil and gas industry [25]. They state that the industry traditionally follows the philosophy that *"given sufficient computing power, we can build a detailed enough model of the decision problem to enable us to calculate the right answer."* They contend that the industry has focused on the downside of uncertainty and not considered the opportunity of creating value by capturing the potential upside. They propose a decision-making process based on a holistic, dynamic approach, combining Monte Carlo simulation with elements from modeling of systems dynamic. Valbuena also highlights the need to exploit the potential upside of the uncertainty [26]. He emphasizes the importance of a decision-making process that *"systematically and consistently addresses the different key drivers that affect the outcome in terms of upside and downside risk."* To support this, he proposes a decision-making process performing trade-off based on the value proposition and the risk to select the best value-risk operation.

Decision-making in the oil and gas industry is often focused on the investment cost, focusing less on the total cost of ownership. Allaverdi et al. concentrate on the lack of focus on the usage context during the early phase [27], stating that this combined with a highly regulated environment leads to a more risk-averse industry that *"endorses system designs that primarily fulfill their initial requirements with limited anticipation and embedment of properties into the system that have long-term value."* They propose a Flexible Design Opportunities (FDO) methodology to systematically and comprehensively account for uncertainty in the early stage of the design process [7].

In the concept selection phase of the oil and gas field development, decision-makers need multi-criteria evaluations to support trade-offs [28]. Multi-Criteria Decision Making tools such as the Pugh Matrix [29] and the Analytical Hierarchy Process (AHP) [30] are the dominating methods used in concept evaluation. Broniatowski [31] states that engineers rely on such techniques to select a subset of designs within a larger trade space. The MCDM serves as an initial concept screening at the system level and is supported by detailed simulation of areas such as flow assurance and electrical analysis [15]. Examples of MCDM methods applied in the early phase of subsea field development are given in [32–34]. Solli et al. propose combining the Pugh Matrix with illustrative ConOps to improve the focus on the operational context during the early stage of concept selection [35]. They find this approach to support stakeholder communication in the early phase, and to serve as a trigger for discovering opportunities and constraints not initially considered.

3.2. Challenges of Decision-Making in Early Phase of Multi-Disciplinary Projects

In the early phase, engineers need to explore business opportunities and needs and develop high-level concepts [10]. Muller states that the stakeholders' concerns should be clarified in this phase, and the key drivers should be captured [36]. Balancing the internal and external key drivers is one of the most critical responsibilities of the system architect in the early phase. Topcu et al. state "*that the essence of systems engineering lies in enabling rational decision-making that is consistent with the preferences of the system's stakeholders*" [37]. The challenge of meeting the stakeholders' preferences and needs is even more challenging when considering systems of systems [38].

Borches [39] presents a survey from the context of magnetic resonance imaging (MRI) systems, exploring the barriers faced when evolving complex systems. He finds the obstacles to be managing system complexity, lack of system overview, ineffective knowledge sharing, finding system information and communicating across disciplines and departments. Similar challenges are reported in the Aberdeen Group's research, a survey of 160 enterprises developing mechatronic products [40]. They find the lack of cross-functional knowledge as the top challenge, followed by the challenge of early identification of system-level problems. They state that problems are often not identified until the physical prototype is developed, highlighting the need for early prediction and models of the system's behavior. The lack of collaboration across technical disciplines is also discussed by Tomiyama [41], categorizing the challenge in three types of difficulties: (i) lack of a common inter-disciplinary language; (ii) the inherent difficulties in dealing with many stakeholders; (iii) multi-disciplinary product development creates inter-disciplinary problems. They link the lack of cross-functional expertise to the challenge of anticipating system problems in the early design stage. Heemels et al. also highlight the lack of a common language between engineers as a challenge in decision-making in the industry [42]. They also identify problems related to the fact that the design choices are made implicitly, based on experience, intuition, and gut-feeling, and highlight the lack of tools and methods to reason about the time-varying aspects during design.

3.3. Use of Systems Engineering Approaches in Early Phase of Subsea Industry

The challenge of technical silos hindering effective systems engineering is often prevalent in interdisciplinary teams [43]. McLachlan [44] claims that silos are one of the obstacles to knowledge transfer in the oil and gas industry and manifest in the inability to deliver value. He proposes using systems thinking approaches to break down the silos. Further, he claims that applying systems thinking can support value creation in the early phases and protect that value through the project lifecycle. Muller et al. state that one of the causes of delays in cost overruns in the subsea oil and gas industry is the complicated information flow, challenging the overview of the system and its interactions [45]. Further, they find that implementing formal methods, such as IDEF0 and SysML, is typically met with skepticism and resistance. Especially in the early phase, formal systems engineering tools are considered too complex and time-consuming for many stakeholders [15,46]. Several case studies from the subsea industry have explored the use of A3 Architectural Overviews (A3AO) in the early phase [16,45–48]. A3AO is a tool developed by Borches [39] to communicate architectural knowledge across disciplines and stakeholders in multidisciplinary projects. One of the strengths of A3AO is the use of visual models to represent systems information, as it communicates to a diverse group of stakeholders [16]. Visual workflows are especially useful when communicating with engineers from the physical domain, such as mechanical engineers [21]. Even if these cases report promise for the use of A3AO in the oil and gas industry, there are challenges related to implementing and using the tool. Løndal et al. find the challenge of implementing A3AO in the existing company processes and tools to be one barrier to usage [47]. Additionally, the resistance to change and the concern of additional work are found to be challenging the industrial application [47,48].

4. Research Method

In this section, we present the research method applied in this paper. Our research is based on action research [49]. We are utilizing the research paradigm industry-as-laboratory [50], where researchers actively participate in the daily work in the industry. The first author has 10+ years of experience in the company. She has worked in the company of research before and during the research presented in this paper.

We collected data through semi-structured interviews, a survey, document study, and observations in the research.

Figure 3 shows the overview of the research method and the way we used the collected data. Initially, we conducted semi-structured interviews to explore the challenges and needs in early-phase work. From the interviews, we identified three themes: awareness of system context, operational scenarios, and key drivers. These three themes formed the basis for the survey. Next, we used data from the interviews and the survey to identify the aspect, extracting the personnel's opinions regarding challenges with existing tools and work processes. In addition, we performed a literature review from cases on the implementation of systems engineering in the subsea industry to extract experience from actual implementations. Finally, the observations from the daily work in the company support the answering of all research questions. The following describes each step of the data collection in more detail.

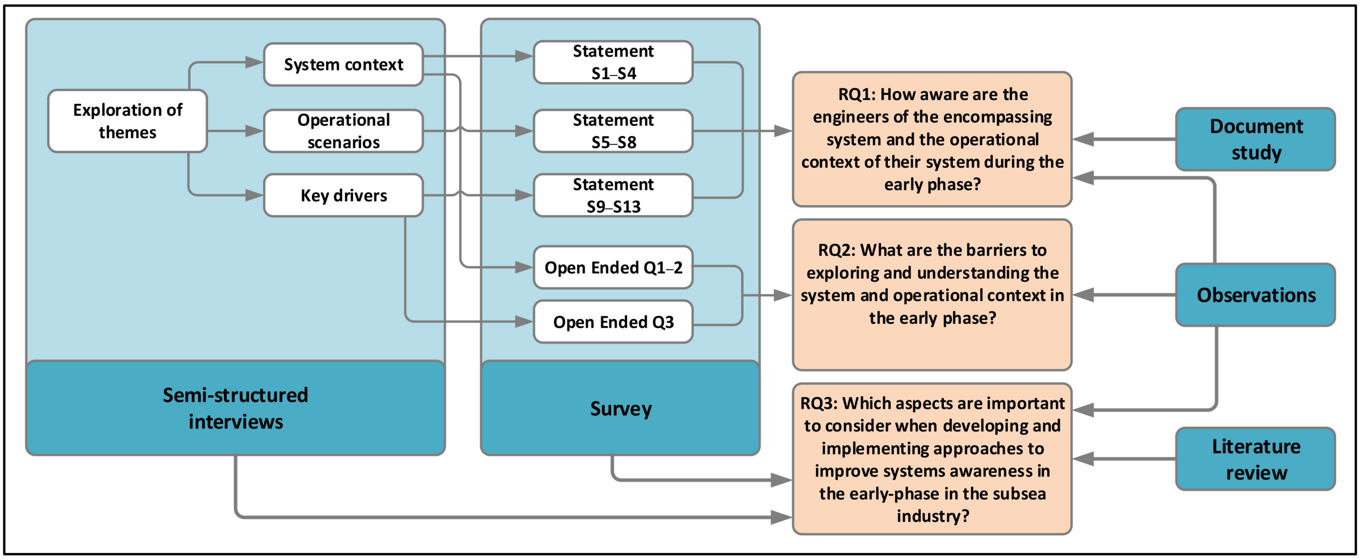

Figure 3. Research method overview.

4.1. Semi-Structured Interviews

In the first phase of this study, we collected data through semi-structured interviews. We used a prepared set of open-ended questions to guide the interviews whilst allowing departures and the exploration of other topics. We recorded the interviews with consent from the participants. The interviews varied from 20–40 min, and in total, we had 3 h and 18 min of recordings. After the interviews, we transcribed all recordings and read through them to familiarize ourselves with the content. As the interview was explorative, the transcripts were not suited for coding. We used the transcripts to explore the challenges and needs in the early phase and identify topics for the survey.

We conducted seven interviews in total. The interviewees were recruited to obtain diversity in the type of experience. Table 1 presents the profile of the interviewees.

Table 1. Profile of the interviewees.

Role	Years of Experience in the Company
Specialist Field Development Engineer	15+
Specialist Field Development Engineer	10+
Senior Field Development Engineer	30+
Senior Field Development Engineer	30+
Senior Systems Engineer	10+
Specialist Systems Engineer	15+
Chief Engineer	20+

4.2. Survey

To elaborate the findings of the semi-structured interviews, we performed a survey with a larger group of company employees. Table 2 shows the target group for the survey.

Table 2. Target group for the survey.

Group	Description
Systems Engineer	Systems engineers, engineering managers, and chief engineers from the field development organization. This group also includes systems engineers from technical disciplines involved in field development studies, including material, technical safety and reliability, and flow assurance
Subsystems Engineer	Systems engineers and lead engineers from the product organization with technical responsibility for subsystem level

We recruited candidates to the survey using the company's organizational chart. The recruitment gave a list of 253 employees, who we invited to the survey. After sending out the invitation, we removed five people from the target group because they found that they did not fit the target group's profile. We also excluded seven subsystem engineers after identifying that the survey was not relevant for their subsystem. The final target group was 241 people, and out of these, 126 responded to the survey. Table 3 shows the number of personnel invited and respondents for each target group, while Figure 4 presents the survey respondents' work experience.

Table 3. Survey response rates.

Group	Invited	Reponses	Response Rate
Systems Engineer	123	74	60%
Subsystems Engineer	118	52	44%
Total	241	126	52%

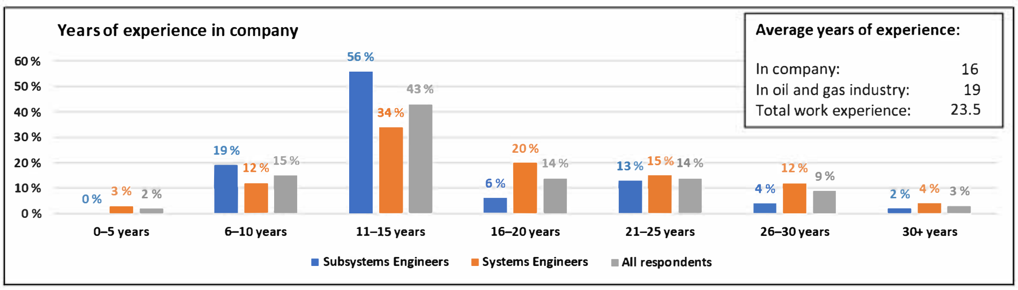

Figure 4. Survey respondents' work experience.

The majority of the survey consists of questions asking the respondent to evaluate statements using a five-point Likert scale [51]. The five-point Likert scale was chosen due to recognizability, as this is the scale commonly used in the company and research in the domain. All statements gave the participants the possibility to answer "I do not know" to skip the question when they did not have the experience or knowledge to respond. We split the survey into sections. At the beginning of each section, we clarified the terms used to reduce the risk of misunderstanding. We used the Net Promoter Score [52] to analyze the responses to the statements, considering strongly agree as a promoter, agree as neutral and neither agree nor disagree, disagree and strongly disagree as detractors. The use of the NPS is a strict assessment, as only "strongly agree" is regarded as a promoter. However, as the statements use "we understand," and "we have sufficient focus", agree is an expected level.

The survey also contained open-ended questions, giving the respondents the option to provide more information on the survey topics. A total of 58 of the respondents gave additional comments—40 from the systems engineering group and 18 from the subsystems engineering group. To analyze the open-ended question, we firstly read all responses to familiarize ourselves with the content. Next, we performed an initial coding, categorizing all responses. We then reviewed the categories and merged them into a smaller set. Finally, we went through the comments once more, coding them with the final set of categories. Table A1 in Appendix A shows the initial and final set of categories we used in the coding.

4.3. Literature Review

We conducted the literature review to identify challenges in the early phase of multidisciplinary projects and experience of the implementation of systems engineering in the oil and gas industry. We mainly used Google Scholar as a source for literature, supported by searches in systems engineering journals. To search for papers on the application of systems engineering in the subsea industry, we mainly used the keywords "subsea," "field development," "front end study," combined with "systems engineering," "systems architecting".

4.4. Observations and Document Study

During the study, the first author was co-located with development teams in the company, gathering data from daily work and discussions, and technical meetings. She took part in ~20 meetings with five different ongoing field development studies. We recorded observations by taking notes. The authors have also reviewed technical documentation as part of the study. Table 4 summarizes the type and number of documents reviewed in the study.

Table 4. Overview of reviewed documents.

Case	Scope of Field Development Study	No. of Documents	Type of Documents
Case 1	Concept for expansion of existing field outside coast of Norway.	4	Internal presentations, Study report, System drawings
Case 2	Concept for subsea system for new field development outside of Canada.	6	Internal presentations, Customer presentation, Study report, System drawings
Case 3	Concept for subsea system for new field development outside coast of Norway.	4	Study reports, System drawings

4.5. Limitation of Research and Validity of Data

We chose a qualitative study as the purpose of the research was to conduct an explorative study. In all qualitative studies, there is a risk of researcher bias and threats to the study's validity. To reduce the bias in our research and increase the results' validity, we used triangulation. Triangulation refers to using more than one method to collect data on the same topic to test validity [43]. We collected our data through interviews, surveys, observations, and document reviews. According to Valerdi et al., a qualitative study should consider the threats to validity [53]. Table 5 summarizes the threats to validity in the data collection and the research's actions to mitigate these threats. A limitation of the research is that the study only considers one company. Thus, it cannot generalize on the challenges in the industry as a whole.

Table 5. Potential bias and mitigating actions.

Potential Bias	Mitigating Actions
Questionnaire design	Pilot-testing questionnaire in two iterations: First with 2 external, second with 2 company employees to remove ambiguously and poorly worded questions. The survey responses were collected for a brief period to reduce risk changes in the external environment during the survey. The survey was open in a total of 38 days.
Sampling	Initial recruitment based on the organization chart. The group managers checked the recruitment group to ensure all relevant personnel were included.
Participants understand nature of research	Everyone who was invited to interviews and the survey received a mail presenting the research's purpose before participating. Before recruiting, we also conducted face-to-face meetings or phone meetings with group managers to ensure clarity in the scope.
Internal validity	Use of triangulation to bypass personal bias of researchers.

5. Results

In this section, we present the results of the study. The results are related to the engineers' systems awareness, the barriers to improving the systems awareness, and challenges with existing approaches and work processes. The following subsection presents results from these three topics, respectively.

5.1. Systems Awareness

First, we present the results evaluating the current systems awareness in the company. We consider the awareness of system context, operational scenarios, and key drivers. The following present the survey results and findings from the document study related to these three items. In the figures, we present the responses for all survey respondents combined. In general, the scores for the systems engineering and the subsystem engineering group are in the same range. Where there is deviation, this is included in the text. Table A2 in Appendix A shows the NPS score for the two target groups for all statements.

5.1.1. System Context

Figure 5 shows the survey results related to the system context. We asked the respondents to evaluate the company's understanding of and focus on the system context (S1, S4) and how their system affects and is affected by other systems in operation (S2, S3).

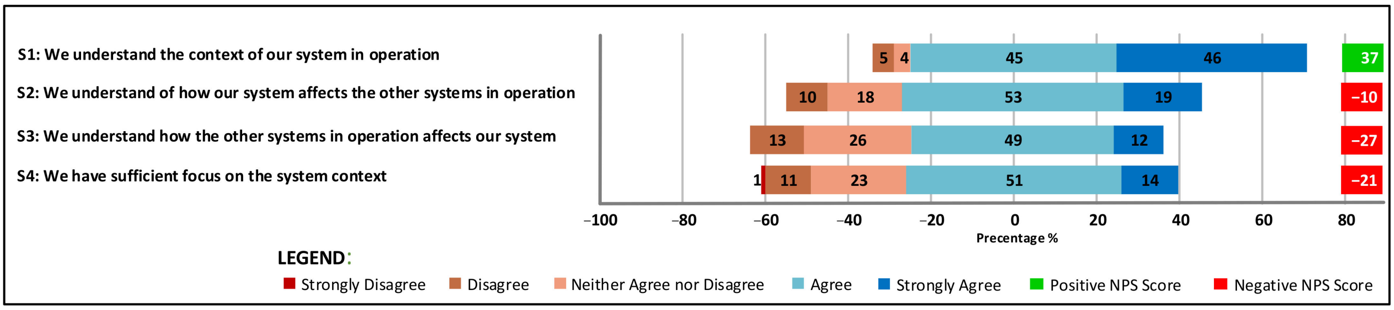

Figure 5. Survey results—systems context.

The results show that the majority agree or strongly agree that they understand their system's context in operation (S1, NPS 37). However, at the same time, the result shows that they are less confident in that they understand how their system affects the other systems (S2, NPS −10) and how other systems affect their system (S3, NPS −27). Reviewing the technical documentation, we find that it does not describe the system's context well, and if discussed, it only considers the static context, that is, what systems are present in operation. The documentation does not give attention to the dynamic context, meaning how the systems in operation interact and affect each other. The findings from the documents correspond with the survey results, showing that the respondents, in general, are aware of which systems are present but not how they interact and affect each other. The survey also shows that the respondents find that they do not have sufficient focus on the context during the early phase (S4, NPS −21). In general, the systems engineers (NPS −15), perceive that the focus on the context is somewhat better than the subsystems engineers (NPS −31).

5.1.2. Operational Scenarios

Figure 6 shows the survey results related to the focus on the operational scenarios.

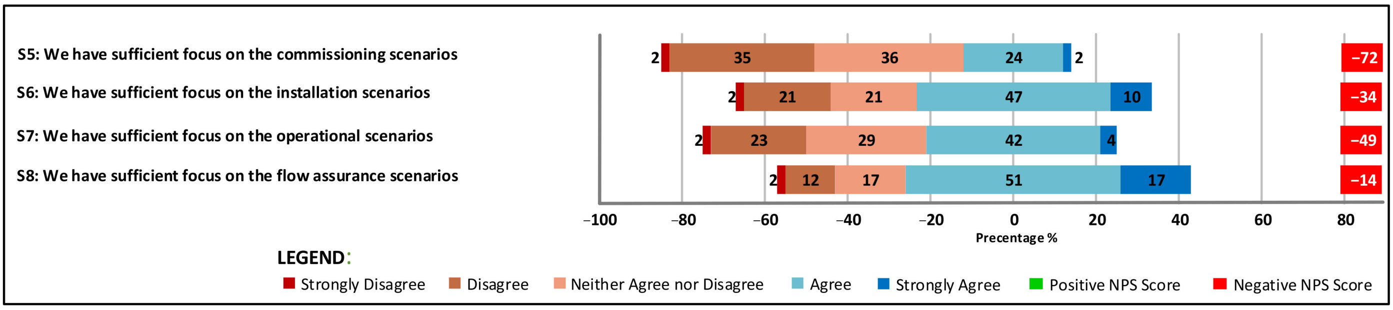

Figure 6. Survey results—operational scenarios.

The main phases in the subsea system operation include installation, commissioning, and operation. The survey result shows that the respondents generally perceive that the focus on operational scenarios is insufficient. The survey shows that the engineers focus the least on the commissioning scenarios (S5, NPS −72), followed by the operational and the installation scenarios (S7, NPS −49, S6, NPS −34). We split the operational scenarios between flow assurance and the other operational scenarios in the survey. Flow assurance evaluates how oil and gas flow in the pipelines; the company treats it as a separate discipline. The survey shows that flow assurance is given the most focus out of the scenarios, but it is still insufficient (S8, NPS −14). There is a significant difference in how the target group perceives the focus for the flow assurance scenario. The subsystems engineers perceive that it is less focused on the flow assurance (NPS, −42) than the systems engineers (NPS, 0).

5.1.3. Key Driver Awareness

Figure 7 shows the survey results related to the focus and awareness of the key drivers. The respondents were given the following definitions of the key drivers:

- An external key driver is the most important need of the customer,
- An internal key driver is the most important need of the company.

From the survey results, we find that the respondents generally perceive the focus on the external key drivers to be insufficient (S9, NPS −32). The survey shows that the internal key drivers are given more priority than the external, but it is still insufficient (S10, NPS −21). Further, the results show an inadequate understanding of how the key drivers affect the solution they propose to the customers in the early phase (S11 NPS −19, S12, NPS −33). In general, the systems engineers perceive the focus and understanding of the key drivers somewhat better than the subsystems engineering group. The survey shows the majority of the respondents find that they have a challenge with balancing the internal and external key drivers (S13, NPS −60).

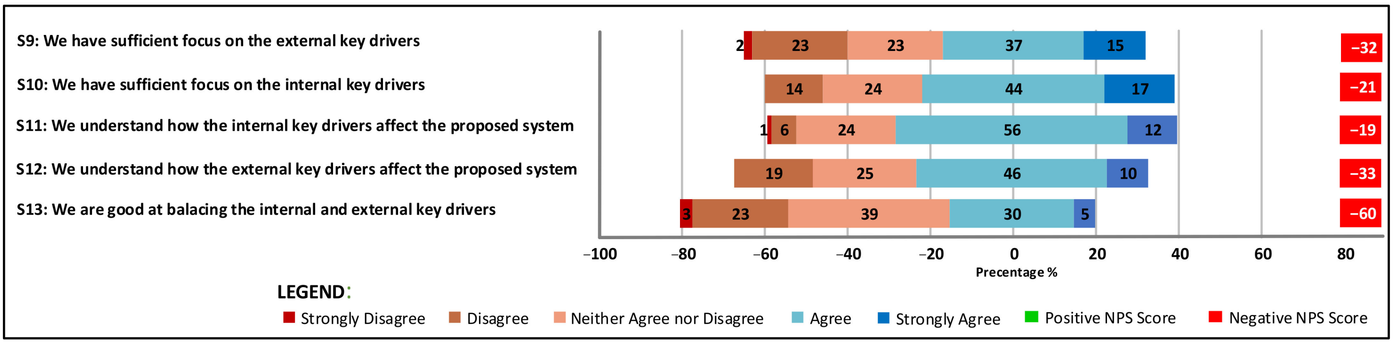

Figure 7. Survey results—key driver awareness.

5.2. Barriers for Systems Awareness

This section presents the results regarding the barriers to systems awareness in the company. We extracted these results from the open-ended questions of the survey. First, we present the result of the coding, identifying the barriers. Next, we present the results for each barrier in more detail, supported by the statements given by the respondents in the survey.

5.2.1. Coding to Identify Barriers

In the survey, we gave open-ended questions to allow the respondents to elaborate on the understanding of system context and key drivers in the early phase. Table 6 presents the open-ended questions asked in the survey.

Table 6. Open-ended questions.

ID	Question
Q1	Do you have anything to add about the company's focus on the context and interactions with the other systems, operators, and suppliers?
Q2	Do you have anything to add about the system understanding in the company?
Q3	Do you have any comments about the company's understanding of key drivers or the balance between external and internal drivers?

In total, 58 of the respondents gave comments on one or several of the open-ended questions. Out of these, 45 respondents commented about the barriers to systems awareness. We coded the 45 comments into the barriers, as shown in Table 7.

Table 7. Barriers for systems awareness.

Category	No of Comments
Lack of a holistic mindset	27
Balancing internal and external key drivers	19
Organizational factors	13
Lack of system knowledge	11
Availability of operational knowledge	9

5.2.2. Lack of a Holistic Mindset

From the coding, we find that the respondents perceive the lack of a holistic mindset as the main barrier for the lack of focus on context and systems understanding in the company. The comments show that the focus is on their system and that the engineers give less attention to their role in the SoS. An engineer from the subsystems group states:

> *"I have the feeling that we have had a too long period with silo thinking, and products and subsystems have too low focus on integrations into a total system."*
>
> Specialist System Engineer, 15+ years of experience

Several respondents highlight that the system understanding is very person dependent, and that it is a challenge to get the engineers involved aligned. An engineer from the systems engineering group states:

> *"Sometimes it is difficult to communicate the system perspective."*
>
> System Engineer, 10+ years of experience

5.2.3. Challenge of Balancing Internal and External Key Drivers

Another barrier reoccurring in the responses is balancing internal and external key drivers. The respondents state that there has been a high push from management recently to utilize standardized products and subsystems, not sufficiently considering if these fit the customers' needs.

> *"We have a strong focus in proposing Solution X without considering the needs and drivers from the customers. This Solution X is not necessarily suitable for the customer and can cause a conflict in the choice of solution."*
>
> Chief Engineer, 25+ years of experience

The respondents express a need for more focus on the customers' drivers and call for more systematic mapping of the drivers. The respondents also highlight that the information they receive from the customers is often rather detailed specifications, making it challenging to identify the key drivers. A respondent exemplifies this:

> *"Parameters affecting the drivers are often buried in a number of specifications referencing other specifications. Often there are conflicting requirements. Clarifications are done early but do not always capture all."*
>
> System Engineer, 13 years of experience

5.2.4. Organizational Factors

Thirteen of the comments identify organizational factors as one of the barriers. The most commented barrier in this category is the distribution of the personnel, both in terms of organizational units and across multiple geographical locations. The responses state that recent company organization changes have enforced technical silos in the company, which is a barrier for cooperation.

5.2.5. System and Operational Knowledge

Finally, we find the lack of system knowledge and availability of operational knowledge as challenges affecting the systems awareness in the early phase. Most respondents acknowledge that most engineers are highly competent in their areas of expertise. However, the respondents state that it is a challenge that too few have knowledge of the overall system. Several respondents link this to the distribution of personnel in the organization, as exemplified by this quote:

> *"We are far more fragmented than before. The number of people that know the overall system is decreasing."*
>
> Chief Engineer, 35+ years of experience

Regarding the availability of operational knowledge, the response shows that it is a challenge to access the operational data, as customers or competitors hold the data. The respondents also highlight that the company previously had little focus on operational knowledge, but lately, the focus has improved.

5.3. Challenges with Existing Tools and Work Processes in Early Phase

This section presents the result regarding the challenges related to approaches and work processes used in the early phase. Table 8 presents the quotes related to this topic. We extracted these quotes from the interviews and the open-ended questions in the survey.

Table 8. Quotes regarding early-phase approaches and work processes.

ID	Quote
[A]	Time is often a limiting factor on how much we can consider [in the studies].
[B]	If we have had 100% success in our studies, we could have documented better. However, when we don't, when we lose many of the studies we perform, it is not justifiable to make so much documentation in early-phase.
[C]	Some of the tools have an extremely high user threshold, making it challenging to get into every time you need it.
[D]	We need to quickly get to a level that "it is good enough."
[E]	I believe we need smaller tools, making it more lightweight and giving the possibility to skip some parts.
[F]	Often, we have too much functionality in tools, so they get too rigid that you no longer actually can use them.

Quote [A] and [B] relate to the challenge of time and effort in the early phase. The studies the suppliers perform on behalf of the client often have short durations, typically 1–3 months. The short deadlines set limitations to how much time the engineers can use in exploration and trade-off. The study phase is also highly competitive, with several suppliers competing for the same contract. The competitiveness leads to several studies not materializing into contracts, as highlighted in quote [B]. To avoid waste, the company needs to balance the effort used in the early phase.

Quote [C], [D], and [E] concern the threshold for methods and tools used in the early phase. Several interviewees stated that the existing tools and approaches used in the company are suited for project execution. These are too rigid and time-consuming in the context of the study phase, and as illustrated in quote [C], it requires too much effort to use them in this phase. The interviewees state a need for tools supporting lightweight explorations, as exemplified in quotes [D] and [E].

Quote [E] also relates to the need for flexibility. It highlights the importance of the ability to adapt an approach to the problem at hand. The interviews reveal that they perceive the existing processes and approaches in the early phase as too rigid. Even if they find the intention behind the tools to be good, the rigidity challenges the use in the early phase, as exemplified by quote [F].

6. Discussion

There is a need to improve the understanding of the long-term effect of the decisions made in the early phase to cope with the changes in the oil and gas industry. Uncertainty highly affects the decisions made in the early phase. Awareness of the system context and the operational scenarios can support identifying operational needs and reducing the risk of late design changes. Improved understanding of the life cycle impact can also support the system suppliers in utilizing the upside of uncertainty to improve their offering [35]. In the study, we find that the system context and operational scenarios are given insufficient focus during the early phase. The study shows that the engineers focus on their system and do not pay attention to their systems' interactions with the other systems in operation. We find that the engineers know which systems are present in the field development but have less understanding of how they operate together to fulfill the encompassing system's capabilities.

We find that the engineers are aware of the lack of focus on the context and recognize the importance of understanding the operational scenarios. Still, they do not improve the focus on the system context and operational scenarios in the daily work. In the study, we identify five barriers the respondents perceive as challenging the explorations and understanding of the system context in the early phase. These include the lack of a holistic mindset, poor balancing between internal strategy and customers' needs, organizational factors, the lack of overall systems knowledge, and the availability of operational knowledge. The lack of a holistic mindset dominates the responses about why the company is not more focused on the encompassing system and the operational context. This barrier is coherent with the observations reported by McLachlan [44], stating that the technical silos are a hindrance to sharing knowledge and creating value. The oil and gas industry has a strong tradition of breaking the systems down into subsystems and products. However, such decomposing introduces challenges to the overall system understanding.

In the study, we find that most engineers are highly competent in their areas of expertise. Still, it is a challenge for them to share and utilize knowledge across disciplines due to the distribution of the personnel in administrative and geographical locations. The engineers state that the allocation of personnel leads to too few people having the overall knowledge of the systems. Consequently, the technical discussions in the study phase are kept at the subsystems level. We observed in the technical meetings that the extensive in-depth discussion on the subsystems level limited the focus on the overall system. The focus on the subsystems carries the risk of unintended system behavior during the integration and operational phase.

The study identifies challenges of balancing internal and external key drivers as another prevailing barrier in the early phase. The subsea production system shall be delivered to a field development and needs to fulfill the customers' needs for the specific field. At the same time, the system is a part of the company's overall portfolio and shall fit into the company's needs and strategies. When there are conflicting needs, the engineers need to make trade-offs to find the solution that best serves internal and external needs. The study shows that the engineers perceive that management is often pushing for solutions that satisfy internal strategy, giving short-term gain, without understanding the long-term impact of their decisions. The engineers are often more aware of the long-term impacts but struggle to communicate their knowledge to the decision-makers. Engen et al. [54] give an illustrative example of this challenge.

The decision-making in the concept evaluation phase requires trade-offs of internal and external key drivers. To support the concept evaluation, the company uses the Pugh Matrix to evaluate and communicate the different options for a concept selection. The study shows a need to improve systems awareness during this concept selection to improve the understanding of the life cycle impact of the decisions. However, for approaches to be applicable in the industry, they need to adapt to the industry's circumstances and needs. We identify four aspects that should be considered when developing and implementing approaches in the early phase of the subsea industry: limited use of resources, adaptability, low threshold of use, and communicating to a heterogeneous group of people.

Limited use of resources relates to the nature of early-phase work in the oil and gas industry. The study phase in the oil and gas industry is highly competitive, and the suppliers expect that a high percentage of the studies will be lost to competitors. An approach for improving systems awareness should add value to decision-making without significantly affecting the time or cost in the study phase.

Adaptability implies that the approach needs to fit within the existing work process and be adaptable to the problem at hand. Implementing new approaches in mature organizations is challenging, even if the approach's value is well known [17]. An aspect highlighted by the engineers is "that no problem is the same," and the scope of the studies in the early phase varies. Approaches to be used in the early phase must have a format that allows them to adapt to the problem at hand.

The third aspect to consider is low threshold of use. The study shows that the respondents perceive existing tools and work processes as rigid and have a too high threshold for early-phase work. The literature shows that implementing systems engineering approaches in the industry is challenged by the fact that engineers perceive them as complex and time-consuming [45,46]. There is a need for methods that have a low threshold to quickly reach a sufficient level of concept exploration without requiring too much effort in learning tools or techniques.

The final aspect to consider is communicating to a heterogeneous group of stakeholders. The study shows a need to communicate systems knowledge both across the engineering disciplines and with the management and other commercial personnel. The literature supports the importance of communicating across the diversity of stakeholders to improve systems awareness [16,45,46]. The literature implies that the use of visualizations supports this communication. Visualizations can support engineers in overcoming the challenges of a domain-specific language and play an essential part in building a shared mental model in the early phase. We have observed in the daily work that engineers respond well to visualizations. In a survey of 44 engineers in the company, we found that most respond that they prefer visual over text-based information for systems activities [16].

The challenge of a lack of focus on system context and operational scenarios has been the subject of several research cases in the last decade [6,16,35,45]. The research presented in this paper adds to the body of knowledge by confirming the challenges reported earlier and exploring the barriers for improved systems awareness in the early phase. In addition, this research identifies four aspects to guide the development of approaches that are applicable for the industrial setting.

7. Conclusions

In the early phase of the system development of subsea systems, the suppliers make decisions that will affect the project's overall profitability. There is a need to improve the focus on system context and operational scenarios to improve the understanding of the long-term impact of the decisions. We have explored systems awareness during the early phase of field development through an in-depth study in a Norwegian systems supplier company. In the study, we find that the engineers perceive that the focus on the context and operational scenarios in the early phase is insufficient. The engineers acknowledge the importance of the system context, yet they cannot apply this in their daily work. We identify the prevalent barriers during the early phase of systems development to be the lack of a holistic mindset and the challenge of balancing internal strategy and customers' needs. There is a need to improve systems awareness during this concept selection to improve the understanding of the life cycle impact of the decisions and mitigate the current barriers. Approaches to improve systems awareness need to be adapted to the industrial setting. We identify four aspects that should be considered when developing and implementing approaches in the early phase of the subsea industry: limited use of resources, adaptability, low threshold of use, and communicating to a heterogeneous group of stakeholders. These aspects can serve as guidance in further work of developing approaches to support early-phase decision-making in the subsea field development study industry.

Limitations and Future Research

Our research is based on action research, utilizing the research paradigm industry-as-laboratory. Action research and similar research approaches are used for systems engineering research to gain an in-depth understanding of the industry's challenges and implement the results from the research in the industry. Such approaches carry the risk of researcher bias. To reduce this risk, we have used triangulation, collecting data from multiple sources.

Another challenge with action research is the challenge of the generalization of research findings. We have conducted our study only in one company, which allows us to go into more detail in exploring the problems and barriers. However, as the study only considers one company, the results cannot be generalized across the industry. Still, we expect the findings to be recognizable and applicable to other companies in the industry, based on our experience working in the oil and gas industry and interactions with practitioners in other companies.

The decision-making in the concept evaluation in the oil and gas industry requires complex trade-offs between multiple criteria. Our study finds that improving the systems awareness can support the engineers in reasoning about the life cycle impact of early-phase decisions. We define four aspects for approaches to be used in the industrial setting to improve systems awareness. Further research should continue to explore how systems architecting can support the improvement of systems awareness in the early phase. The aspects proposed in this paper can serve as guidance to develop and evaluate approaches that are applicable in the industrial setting.

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Appendix A

Table A1 shows the categories used for the coding of the open-ended questions in this study.

Table A1. Categories for coding.

Category	Sub-Categories
Lack of a holistic mindset	Lack of contextual/overall focus Lack of focus on systems understanding Focus on subsystems/parts Need for more system thinking
Balancing internal and external key drivers	Challenges related to strategy Conflicting interest in company Lack of customer focus Balance of internal and external needs
Organizational factors	Distribution of personnel geographically Distribution of personnel in organization Technical silos Poor manning
Lack of system knowledge	Detailed focus Subsystem and part knowledge Too few know the overall system
Availability of operational knowledge	Availability of data Lack of focus on operational knowledge Poor knowledge transfer between phases

Table A2 shows the NPS scores for each target group for comparison.

Table A2. NPS score for each target group.

Statement	NPS All Respondents	NPS Systems Engineer	NPS Subsystems Engineer
S1—We understand the context of our system in operation	37	36	38
S2—We understand how our system affects the other systems in operation	−10	−7	−14
S3—We understand how the other systems in operation affect our system	−27	−26	−29
S4—We have sufficient focus on the system context	−21	−15	−31
S5—We have sufficient focus on the commissioning scenarios	−72	−66	−81
S6—We have sufficient focus on the installation scenarios	−34	−33	−34
S7—We have sufficient focus on the operational scenarios	−49	−47	−55
S8—We have sufficient focus on flow assurance scenarios	−14	0	−42
S9—We have sufficient focus on the external key drivers	−32	−30	−36
S10—We have sufficient focus on the internal key drivers	−21	−16	−30
S11—We understand how the internal key drivers affect the proposed system	−19	−13	−30
S12—We understand how the external key drivers affect the proposed system	−33	−25	−42
S13—We are good at balancing the internal and external key drivers	−60	−62	−57

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Article 4

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Conceptual Models to Support Reasoning in Early-phase Concept Evaluation - a Subsea Case Study

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***Abstract*— This paper shows how conceptual models can support the reasoning during early-phase concept evaluation in the subsea domain. Proposing concepts that are fit for purpose requires subsea companies to carefully balance conflicting needs in a complex system of systems. To support this balancing, there is a need to improve the understanding of how the needs affect the system through its life cycle. Through a retrospective case, the paper demonstrates how the visualization of dynamic behavior supports engineers in reasoning about the impact of the key driver and design decisions. In this case, we use concept mapping to visualize the customer and subsea company drivers. We identify the key drivers and the tensions between them from the mapping. Furthermore, we use abstract workflows combined with timelines to explore how the design concepts will affect the key drivers throughout the systems life cycle. The lead engineer responsible for the study appreciated our approach to supporting reasoning during concept evaluation. He claimed that the conceptual models communicated what he had used more than 40 slides to explain to the company's management to get a decision. We conclude that this approach and models are well suited for internal communication and support a common understanding across the organization.**

Keywords—Conceptual models, Concept evaluation, Dynamic behavior, Key drivers, Subsea domain, Visualization.

I. Introduction

In the early phase of the systems life cycle, system engineers explore feasible concepts and make design decisions. The decisions made in this phase have a significant impact on the resulting system design and realization[1]. As the cost of change becomes increasingly expensive as the system design matures, making the correct design decisions in the early phase is key to making the system development viable [2], [3]. We have performed our research within the subsea domain, considering the early phase of development of subsea production systems. The subsea production systems are complex, operate in harsh environments, making the repair and maintenance activities costly and time-consuming [4]. The challenging operational environment makes it increasingly important to consider the life cycle needs in the early-phase design. Nevertheless, life cycle considerations often have lower priority than minimizing initial capital expenditure in this industry [5]. A major reason for cost overruns in the subsea industry is late design changes, which often relate to poor consideration of the operational needs in the early phase [6], [7].

In the early phase of the field development, the subsea suppliers develop system concepts on behalf of their customers. These concepts shall fit the customer's need for the specific project and at the same time align with the company's overall strategy. Often the customer and the company have conflicting needs. To support balancing conflicting needs, there is a need to improve understanding of how the decisions made in the early phase affect the system through its life cycle.

To support the decision-making, we propose using conceptual models to reason about the system's dynamic behavior and how qualities emerge in the interactions between the systems. We define dynamic behavior as the interaction between the parts and the context over time. For companies adapting to a model-based system engineering regime, the system's behavior is typically captured in behavior diagrams such as use case, activity, and sequence diagrams[8]. However, the oil and gas industry is immature in applying model-based systems engineering [9]. Research from the domain shows that more formal system engineering approaches are often perceived as time-consuming and not applicable, and are typically met with skepticism [10]. Research from the domain shows that more formal system engineering approaches are often perceived as time-consuming and not applicable and are typically met with skepticism [11]. Muller et al. have proposed the use of visualization conceptualize the system's dynamic behavior [12]. Several studies from the oil and gas domain have shown that the industry practitioners respond well to visual and conceptual models [13], [14].

This paper presents a case study applying conceptual models to an early phase study in the subsea domain. The case is exploring a recently conducted early-phase study in the company. First, we use concept mapping to visualize the customer and subsea company drivers. From the mapping, we identify the key drivers and the tensions between them. Next, we explore these tensions using conceptual models. In particular, we use abstract workflows combined with timelines to explore how the design concepts will affect the key drivers throughout the systems life cycle. We find that our approach supports the engineers in reasoning and communication during the early-phase concept evaluation.

The context for this paper is the early phase of projects in the subsea domain. The INCOSE Systems Engineering Handbook [15] provides an overview of the generic life cycle stages, as shown in Fig. 1. Our work is within the exploratory phase. The main activities in this phase include defining the problem space, characterizing the solution space, identifying stakeholder needs, and exploring feasible concepts. **Clarification of terms.** We have conducted our research within a subsea company, developing and supplying subsea production systems to the oil and gas field developments. To avoid confusion of terms, we hereby call the subsea company the "company." The oil and gas companies that operate the fields and request the concept study from the company, we hereby call "customer."

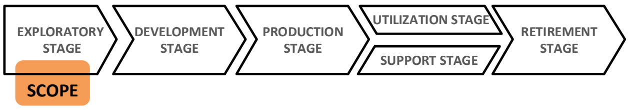

Fig. 1. System life cycle

II. RELATED WORK

Decision-making is widely discussed in the literature and is explored across a range of domains, including business, health, and education [16]. The process of decision-making consists of generating alternatives, evaluating them, and choose the most suitable concept. Hallo et al. state that the decision-making process is a cognitive process that can be rational or less rational and driven by explicit knowledge, implicit knowledge, or one's belief systems [16]. Robinson et al. also emphasize the cognitive process's role, stating that "*decision-making is a multifaceted, socially constructed human activity that is often non-rational and non-linear"* [17]. An essential aspect of decision-making is balancing the stakeholder's needs. Topcu et al. state that *"the essence of systems engineering lies in enabling rational decision-making that is consistent with the preferences of the system's stakeholders"* [18]. The challenge of meeting the stakeholders' preferences and needs is even more challenging when considering systems of systems [19], [20].

According to Simmons [21], decision support is the "*task of assisting decision-makers in making a decision"*. He split between programmed decisions, characterized as "*routine, well-defined, can be modeled and optimized precisely* and *solvable by established procedures",* and non-programmed decisions, characterized as *"non-routine, weakly-defined, usually significant impact* and *often solved by heuristics search of general problem-solving methods"*. The first group is typical decisions in Engineering Design, while the second group is typical decisions in Systems Architecting. In his thesis, he presents a framework for decision support called Architecture Decision Graphs (ADG). The context for their work is space missions. A similar architectural framework for analyzing spatial and temporally distributed resource extraction systems is given by Alikbargolkar and Crawley, using the offshore production field as an example. Bijlsma et al. give an overview of quantitative reasoning methodologies to support architectural decisions [1]. They state that these approaches often are focus on software. Of the methods focusing on the system-level decision-making, they include BoDerc [22], ArchDesigner [23], and Geeglee [24]. The same paper presents a decision support methodology for evolutionary, focusing on embedded systems [9]. This methodology consists of three elements: a *structure* to model the systems qualities and system realization, a *method* for reasoning and decision-making, and a *formalism* to express the structure. The BoDerc design methodology was proposed to support the development of high-tech systems within industrial constraints [22]. They state that typically, challenges in decision-making are lack of common language between engineers and that the design choices are made implicitly, based on experience, intuition, and gut-feeling. They also highlight the lack of tools and methods to support the understanding of the time-varying aspects in design. Their method provides two means. Firstly, identify the most critical issues to ensure focus on the essential conflicts and tensions in the design decisions. Next, they propose using simple models to create insight within a reasonable time, adapting the detail level to the accuracy of the answer needed.

Renzi et al. present a review of the state of art and classification of decision-making methods in industrial design [25]. They identify three main groups of decision-making for solving engineering design problems; Multi-Criteria Decision Making (MCDM), Problem Structuring method, and Decision-making Problem-solving methods. Multi Criteria Decision Making (MCDM) provides strong decision making in domains where the choice of the best alternative is highly complex [26]. Broniatowski [27] states that engineers rely on techniques to support in selecting a subset design within a large trade space, and techniques like Pugh Matrix [28] and Analytical Hierarchy Process (AHP) [29] are commonly used. Although such methods are widely used in industrial applications [25], [26], they have several shortcomings. Xu states that such methods lack focus on the decision's uncertainty, stating the *outcomes from analyses based on such models appear to be free of uncertainties, which could be misleading to the inexperienced* [20].

Åslie et al. state that the concept select phase of a subsea field development requires the decision-makers to do trade-off, and the multi-criteria evaluation is essential [30]. Their work reviews the current state of decision-making in the early phase of oil and gas field development and finds Multi Criteria Decision Making to be the dominating method for support concept evaluation. Cases from the subsea industry, [13], [14], [31], show that conceptual models are useful to support the reasoning during the decision-making process. Common for all these cases is that the problem they explore in the model is defined beforehand, based on experience or stakeholder input. The cases give no guidance on identifying the most important issues to investigate. In our work, we find inspiration from the BoDerc design methodology [22] and first identify the most significant tensions during the decision-making to identify the most important problem to explore. We next use the conceptual models to investigate the problem, to support the reasoning and a mutual understanding across the diversity of stakeholders.

III. CONCEPTUAL MODELS

Modeling is a central activity in systems engineering to understand and simplify reality through abstraction. Ramos et al. [32] state that state that *"from brain representations to computer simulations, the models are pervasive in the modern world, being the foundation of systems' development and systems' operation."* A conceptual model is an abstract, simplified representation of a system of interest [33]. Fujimoto et al. state that as all models are a simplification of the real world, all modeling involves conceptual modeling [34].

Lavi et al. state that in model-based systems engineering, a conceptual model is the product of the system representation process [35]. Further, they state that conceptual modeling facilitates the system design process by allowing for a shared representation of system architecture, helping to manage complex knowledge and resolve conflicts and ambiguities. Dori [36] emphasizes the role of the human in the modeling, stating that *"models show certain aspects of that reality, including function, structure, and dynamics, as perceived or envisioned by the human modeler or system developer*".

An important field of application for conceptual models is within simulations. A commonly used definition of conceptual models is given by Robinson [37], stating that *"the conceptual*

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model is a non-software specific description of the computer simulation model (that will be, is or has been developed), describing the objectives, inputs, outputs, content, assumptions, and simplifications of the model." However, it is not a widely accepted definition or understanding what the conceptual model is [39] within the field of simulation [38]. In [39], five leading researchers within the field discuss their views and beliefs on conceptual modeling, highlighting the lack of common ground. Hoppenbrouwers et al. [40] give a contribution to the definition of conceptual modeling, focusing on the process of creating the models. They state that the goal of modeling to reach a state where all participants have some degree of shared understanding. There is a need to facilitate the communication and knowledge sharing between domain experts and modelers to enable this.

The conceptual model is a central part of Checkland's Soft Systems Methodology (SSM) [41]. The SSM splits between the 'real world' and 'systems thinking' activities. The systems thinking activities contain the 'root definition' and 'conceptual model'. The root definition is a concise construct of a human activity system, stating what the system is. The conceptual models elaborate on what the system does, based on the root definition. In this methodology, the conceptual models are used to make a structured investigation of a 'real world problem'. Checkland emphasizes that the conceptual model should be *"seen as 'hows' rather than 'whats'.."* and that *"building conceptual models is a matter of experience and skill"* [42]. Another conceptual model from system thinking is Boardman's systemigram [43]. Systemigrams are used for understanding and identifying significant elements of the system of interest, representing the interrelationships and diverse expression of stakeholder concern and needs [8]. McDermott states that conceptual models can be used to capture higher-level textual or descriptive models of the problem that can then be decomposed into lower sets of measures that can be assessed analytical [44]. He highlights the importance of the human's ability to move between analytical and conceptual models. At the same time, he introduces the challenge of visualization to get the appropriate linkage between high-level conceptual representations and low-level analytics.

We build our research on the work of Muller [45]. He states that conceptual models "*are models that are sufficiently simplified to help architects to understand, reason, communicate and make decisions"* [46]. Further. he defines conceptual models as a hybrid of empirical and first principle models [47]. Empirical models describe what we observe and measure, while first principle models explain the behavior of a property, using first principles from science, such as laws of physics. He emphasizes the need for the conceptual models to be *"simple enough to understand and to reason, while it must be realistic enough to make sense".*

IV. THE CASE

A. Research Method

In our research, we are utilizing the research paradigm industry-as-laboratory [48], where researchers actively participate in the daily work in the industry. The purpose of this paper is to report the experience of using conceptual models to support decision reasoning. In the case we present in this paper, we apply the models to an actual study ongoing in the company. We have collected the data through existing technical documentation and informal interviews with key resources working on the study.

B. A Short Introduction to Subsea

Installation and operation of subsea oil and gas fields require interaction between many constituent systems and a

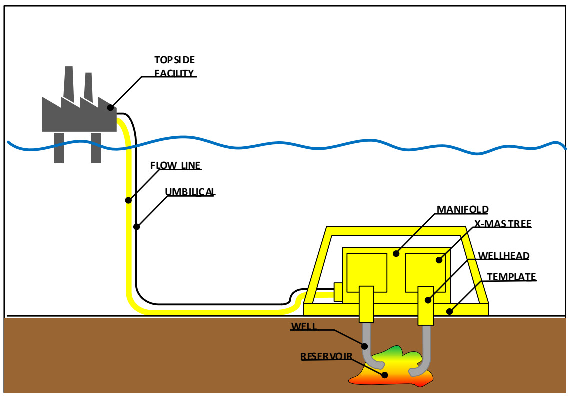

Fig. 2. Illustration of the subsea system

diversity of actors. The INCOSE Oil and Gas working group finds the complexity of a field development comparable to chemical plants, aircraft, or space missions [11].

A subsea field development starts with discovering trapped oil or gas in a reservoir. To develop the field, the operator drills wells from the seabed to the reservoir and install a subsea production system. The purpose of the subsea production system is to transfer the oil and gas from the bottom sea to a topside or an onshore facility. Fig. 1 shows a simplified sketch of a subsea system, and in the following, we present the most critical sub-systems..

A **wellhead** is a pressure-containing interface between the well and the X-mas tree.

A **X-mas tree** (XT) is an assembly of valves and piping, which acts as and pressure barrier between the well and the environment. The XT is used to control the flow of oil and gas from the well. The XT includes a control module to control the valves on the tree and downhole and collect signals from the manifold and topside/onshore facilities.

A **manifold** collects, handles, and distributes production fluids from several wells. The manifold also includes a control module to control the manifold valves and collect sensor information.

An **umbilical** supplies electrical signals, chemicals, and hydraulic services between subsea equipment and topside/ onshore facility.

The **flowlines** transport the production from the subsea production system to the topside/onshore facility.

C. Introduction to the case

In the following, we present the case study. We have considered an early-phase study recently conducted in the company. The scope of the study was to propose concepts for expanding on an existing subsea field. While presenting the case, we have changed the naming and data due to confidentiality.

1) The field

The Dolly field is located on the Norwegian Continental Shelf, 100 km west of the coastline of Norway. The water depth at the location is 1000-1200 meters. The area is known for having a harsh operational environment with high waves and currents. It is a gas field and has been in production since early 2000. The existing infrastructure at the field is an on-template system. Currently, four 6-slot templates are installed with Horizontal X-mas Trees. The field produces back to a

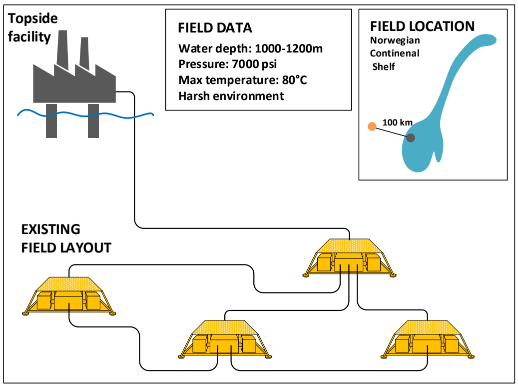

Fig. 3. Field data

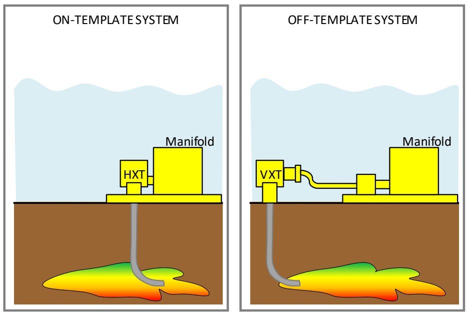

Fig. 4. Alternatives for field expansion

topside facility. Fig. 3 shows an illustration of the field layout and its key data.

2) The study

Currently, there are well slots available on some of the templates in the field. To increase production, the customer wants to install two additional wells at the field. They are evaluating two alternatives for expanding the field:

- An ***on-template system*** with horizontal X-mas trees (HXT), which means the XT is installed directly at the template and tied into the manifold. This is the solution used for the system already installed at the field.
- An ***off-template system*** with vertical X-mas trees (VXT), which means that the well is drilled and the XT is installed some distance from the template. This solution requires additional flowlines from the VXT to the template. The flowlines are tied into the manifold through the existing well slot.

Fig. 4 shows an illustration of the two alternatives. The customer asked the company to perform a study evaluating these two alternatives to expand the field. The technical study team performed a study, concluding that the on-template system was the preferable system for the customer. However, offering an on-template solution conflicted with the company's overall strategy. The engineering team spent much time convincing the management that an on-template system was the preferable solution for the field extension. We have conducted our study in retrospect to show how conceptual models could have supported the engineering team in the communication with the internal stakeholders. In the following, we will present the models we developed.

D. Modeling

1) Identification of tension and issues

To understand the tension and issues to explore by modeling, we need to understand the key drivers. The project has identified more than 20 drivers for the field development, but the documentation did not provide information on which are most important. To identify the key drivers, we organized the drivers using concept maps [17]. A concept map is a graphic diagram for organizing and representing knowledge [18]. Fig. 4 shows the final map of the drivers. In the figure, the nodes represent drivers, and the links contain information on how they relate to each other. We made separate maps for the customer and the company drivers. The company map includes the project-specific drivers and overall drivers related to the company strategy across the project portfolio.

We used the mapping to explore the relationship between the drivers through several iterations with the lead engineer. During the mapping, we found that the engineering team had more information on the drivers' background, which was not available in the existing documentation. We chose to include this information in the concept map to make the knowledge available for others.

We defined four customer and four company key drivers from the mapping, as shown in darker colors in Fig. 5. The customer needs to maintain the field production, to keep the field profitable. To achieve this, they need additional production wells. At the same time, a low cash flow in the project is a challenge. This drives the need for a quick start-up, leading to a need to *minimize the risk of schedule delay* to meet the available time slot of the vessel. Due to the low cash flow, the customer wants to keep investment costs down, which drives the need for *minimizing installation cost* and *minimizing hardware cost.*

The company's overall key drivers are to *utilize the company's* preferred solution to standardize their deliveries across the project portfolio and *secure contracts*. The project-specific drivers are *the availability of workover equipment*[1] and *tooling*[2] *synergie*s, as the use of legacy equipment will position the company to be the service provider through the life of field.

Next, we mapped the relation between the identified key drivers and the two alternative concepts, as shown in Fig. 6. We started with linking the company drivers to the concepts. This shows the overall conflict, that the overall drivers call for an off-template system while the project specific drivers push for an on-template system. We then added the links between the design concept and the customer key drivers. The black arrows indicate which concept is assumed to be the better based on general knowledge of the concepts and represent the typical evaluation the management would make. The brown arrows indicate which concept is assumed to be better based on the project-specific knowledge. We find there is a conflict between the general evaluation and the project specific related to two of the key drivers, namely, *minimize the risk of schedule delay* and *minimize installation cost.* These conflicts are highlighted in the red circles in Fig. 6.

[1] Workover equipment are the riser system and associated tooling to perform operations such as maintenance and repair on the wells

[2] Tooling is a general term for all tools used to support the installation and operation of the subsea system, such as connection, lifting and cleaning.

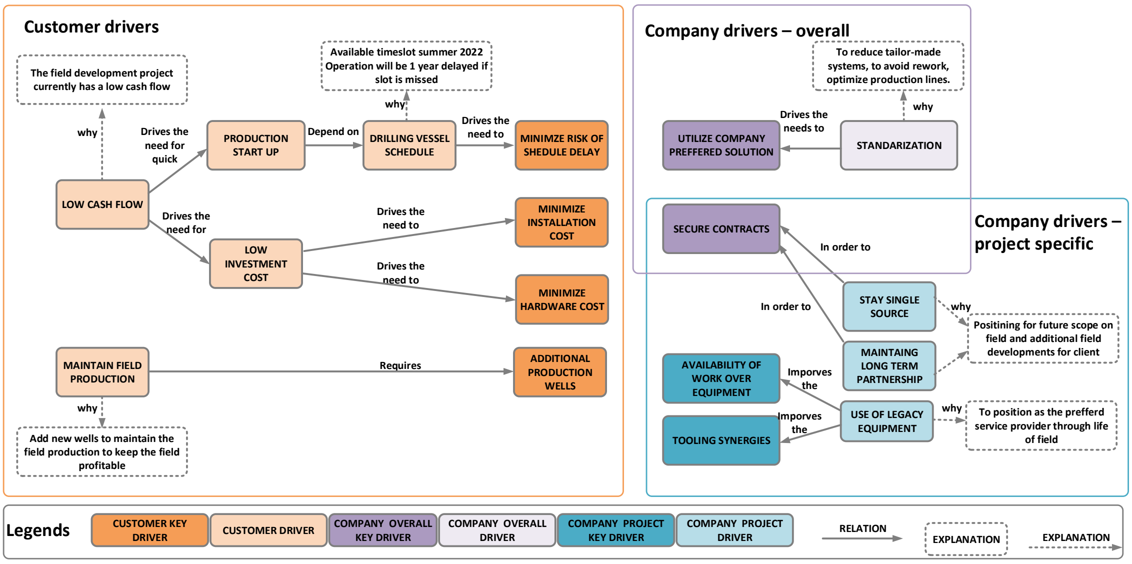

Fig. 5. Key driver mapping

2) Modeling of life cycle impact

Our next step was to use visual models of the dynamic behavior to support the exploration of the conflicts. As seen in the key driver mapping, the conflicts relate to the mismatch between the generic knowledge of the concepts and the project-specific knowledge. We started with mapping the generic workflow for a subsea system from engineering through operation, as shown in Fig. 7. After discussing the study lead, we found that the concepts differ the most in the installation phases. Therefore, we made a breakdown of the drilling and commissioning phase, as shown in Fig. 8. We first made the models based on the generic knowledge of the operation to get an overview of the general assumptions for evaluating the concepts. We used an abstract workflow to show the flow of the events for the two different concepts. For each of the workflows, we added a timeline showing the duration of the different activities. We also add constraints and concerns associated with the workflows in the model.

The model shows why the off-template solution is assumed better to minimize the risk of schedule delays and minimize the installation cost. As seen in the model, the on-template system is dependent on the delivery of the HXT to complete the well. This raises concerns about the risk of delays in the HXT delivery. The timelines also show that the duration of the off-template solution is somewhat shorter, making it the preferable concept to keep the installation cost low. The next step in our modeling was to make the generic workflow project-specific by adding the knowledge of the engineers in the study team. Fig. 9 shows the model with project-specific information.

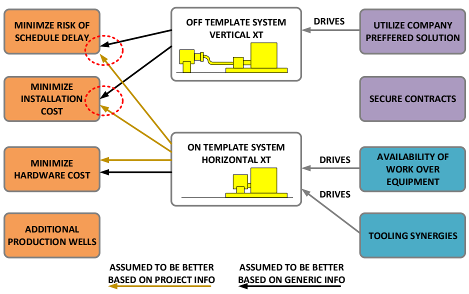

Fig. 6. Relation between key drivers and design concepts

We started with adding the project-specific constraints to the activities in the workflows and mitigating actions. Next, we updated the workflows and timeline to account for the effect of the identified constraints. As the model shows, the workflow and timeline for the on-template solution are the same as is in the previous model. For the constraints regarding the XT, we added a mitigation action; since this is the existing solution in the field, the customer can use available spares if there is a delay in the XT delivery.

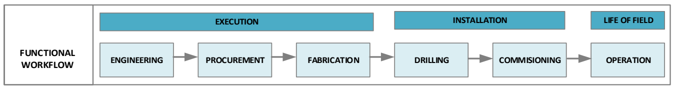

Fig. 7. Overall workflow - subsea system life cycle

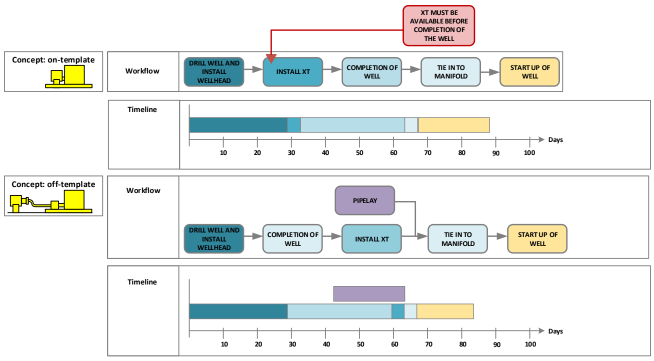

Fig. 8. Model - generic knowledge

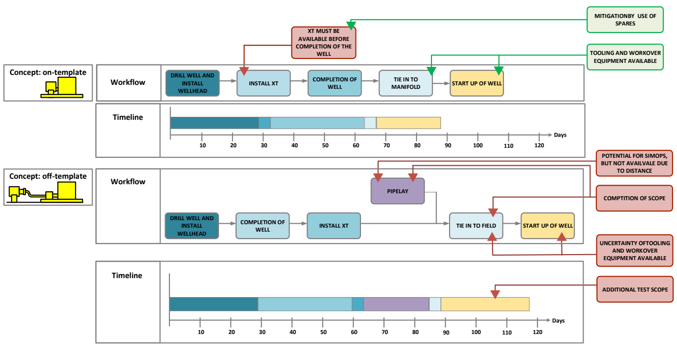

Fig. 9. Model - project specific knowledge

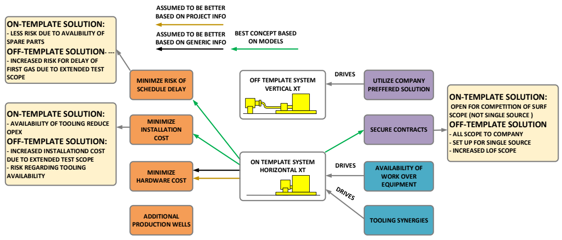

Fig. 10. Key driver map with findings from modeling

There are more changes to the workflow and timeline for the off-template systems. Firstly, the off-template solution requires pipe-laying activities. The general assumption is that pipe laying can be done in parallel with the drilling and completion of the well. However, in this case, the distance from the off-template well to the template is very short, making it impossible to have two vessels operating simultaneously. Consequently, the pipe-laying will increase the overall duration of the installation. The duration of the timeline is also increased for the startup of the well, as the off-template solution is a new system on the field and would require additional test scope. It also increases the risk of delays in this phase, as it introduces a dependency on tools and work equipment, which are not available in the legacy equipment. In addition, the off-template solution introduces more pipe laying activity, which is not within the scope of the contract. The increased scope would be open to competition, and the company risks that they are no longer the single source.

3) Combining models for documentation

In the last step, we included the findings from the modeling into the key driver mapping. Fig. 10 shows the combined map. We used green arrows to indicate the concept that the modeling showed was best for the given driver. To show the reasoning for the linking, we included the main findings for both concepts. The links between concepts and drivers we have not explored we kept as before in the model. This serves a purpose as documentation to give resources in later phases an insight into which links are based on assumptions and explored in the modeling.

V. Discussion

In the case study, we show how conceptual models can support the exploration of the impact of early-phase project decisions. We have considered a recently conducted early-phase study in a subsea company. From technical documents, presentations and meetings with the lead engineer, we found disparate information about drivers for the concept evaluation. We mapped these drivers using concept maps. The mapping supported the understanding and identification of the key drivers. By relating the key drivers to the alternative concept, the conflict between the drivers imposed by the company strategy and the project specific drivers became evident. While doing this mapping, it became obvious that the management makes their evaluation based on the generic knowledge of the concepts. The engineering holds project-specific knowledge but struggles to communicate this knowledge to the management effectively.

To explore the tensions between the company strategy and the project key drivers, we used conceptual models to reason about the impact of the concept choice throughout the systems life cycle. We used abstract flows to describe the main activities in the life cycle. As time was an important aspect, we also included timelines to visualize the duration of the activities. We tried other types of visualization during the modeling, such as concrete "cartoon" workflows and swimming lines [12]. We found the abstract workflows and timelines to support the problem at hand. Previous research has found that these types of models are well perceived by the engineers within the subsea domain [13], [31]. Through the models, we explored the system's interactions through its life cycle. The models focus on how the two alternative concepts affect the system over time. First, we modeled based on the generic knowledge; that is, "what everyone knows." The purpose of this step was to achieve a common understanding of how the management perceives the concept evaluation. Next, we added on the project-specific constraints and modeled the impact on the timeline. The project-specific models give a simple overview of the actual constraints in the study.

Supporting the reasoning and communication in the early phase was the focus in our study. In addition, we find that the models can provide documentation of the early-phase decision for later design phases. In previous work, we have found that the documentation from the early-phase in the company mainly describes "what the system is" rather than "why the system is as it is." In the early-phase, the concept evaluation is typically captured using Pugh matrices [6]. We anticipate that the models we propose in the case can be linked to the Pugh matrices to improve the quality of the documentation.

In the paper, we have used visualization as a tool to conceptualize system behavior. While many initiatives are ongoing on Model-Based Systems Engineering in the subsea domain, the industry is still immature in implementing formal system engineering methods and techniques [9]. Previous case studies from the subsea domain have shown that the use of informal models is well perceived in the industry, especially for communicating across the diversity of stakeholders [13], [14], [31]. The use of visual, conceptual model is not an alternative, but a supplement to Model-Based Systems Engineering methods [12]. The use of informal conceptual models in the early phase supports the engineers in reason about the system's behavior, and can make a foundation for more formal modeling in later phases of the system development [6].

VI. Conclusion and Future Work

In this paper, we have shown how conceptual models can support the reasoning during early-phase concept evaluation in the subsea domain. Through a systematic approach, we first analyze the key drivers to identify the tensions and conflicts. Next, we use conceptual models to explore the impact of the drivers throughout the systems life cycle. The models presented in this paper support the reasoning and serve as communication across a diversity of stakeholders. The lead engineer responsible for the study was very positive about the systematic approach to reason about the concept evaluation. He found that the model with project-specific information (Fig. 9) in an easy manner communicated what he used over 40 slides to convince the management. He also stated that this approach and these types of models would also be helpful in communicating with other internal resources, to explain how their part of the scope interacts and their role in the system as a whole.

This case study aimed to show how conceptual models can support the reasoning regarding the key driver impact. In this case, the modeling was done retrospect by the researcher, not by the engineers working in the industry. The engineers involved in the work have given positive feedback to the approach and the models. Further research is needed to evaluate the value of the approach and the use of conceptual modeling in the industry.

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Article 5

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