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Siv Engen
University of South-Eastern Norway

Kristin Falk
University of South-Eastern Norway

G. Muller
University of South-Eastern Norway

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Article

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

Siv Engen *, Kristin Falk and Gerrit Muller

Faculty of Technology, Natural Sciences and Maritime Sciences, University of South-Eastern Norway, 3610 Kongsberg, Norway; kristin.falk@usn.no (K.F.); gerrit.muller@usn.no (G.M.)
* Correspondence: siv.engen@usn.no

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.

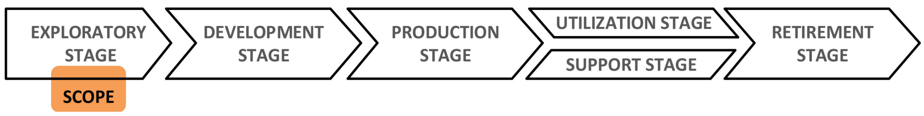

Figure 1. Relation of our work in the INCOSE life cycle stages.

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.

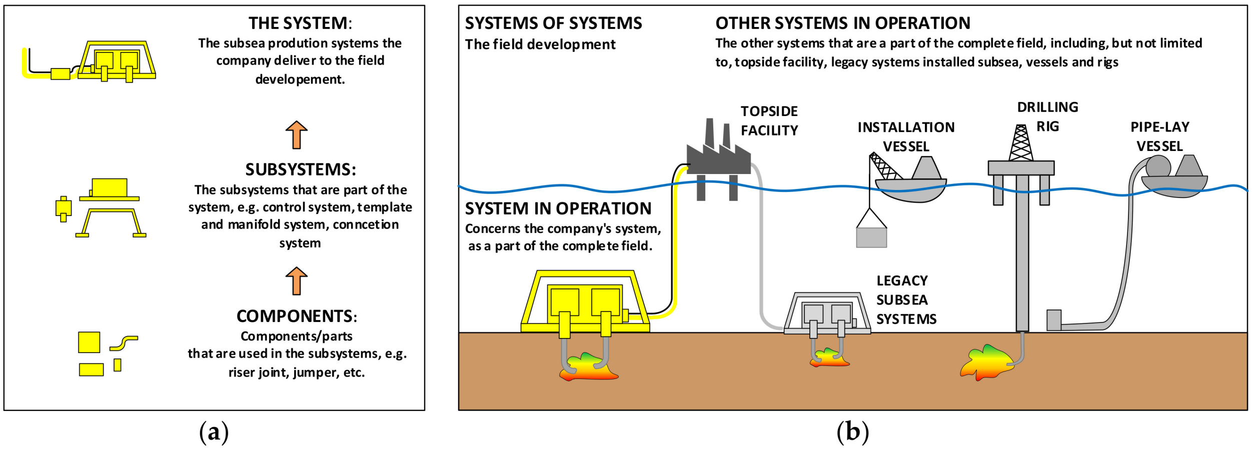

Figure 2. (**a**) Relation and definition of the system, subsystems, and products. (**b**) Relation and definition of the super system, the system in operation, and the other system in operation.

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.

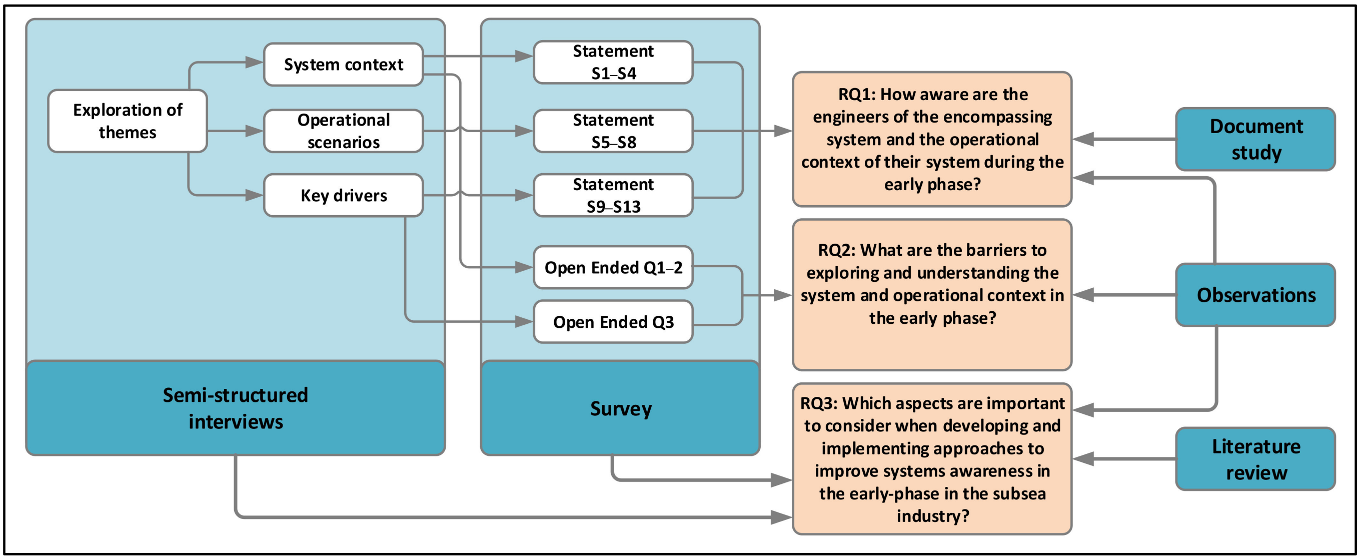

Figure 3. Research method overview.

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%

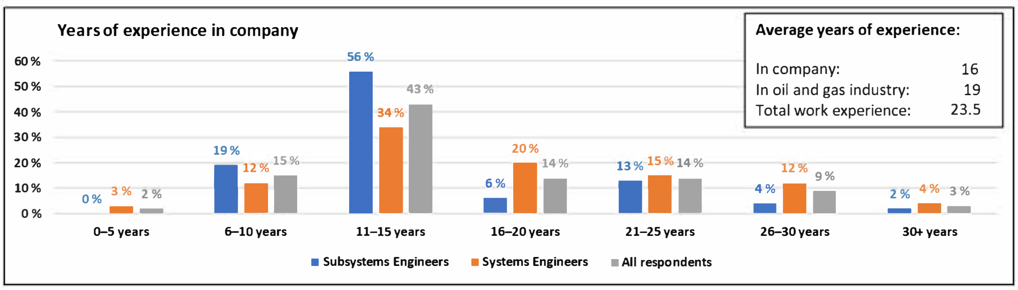

Figure 4. Survey respondents' work experience.

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).

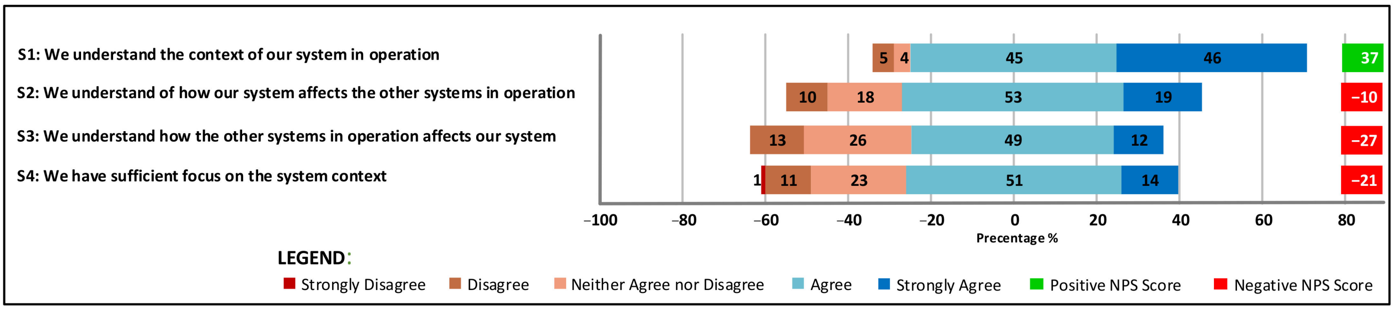

Figure 5. Survey results—systems context.

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.

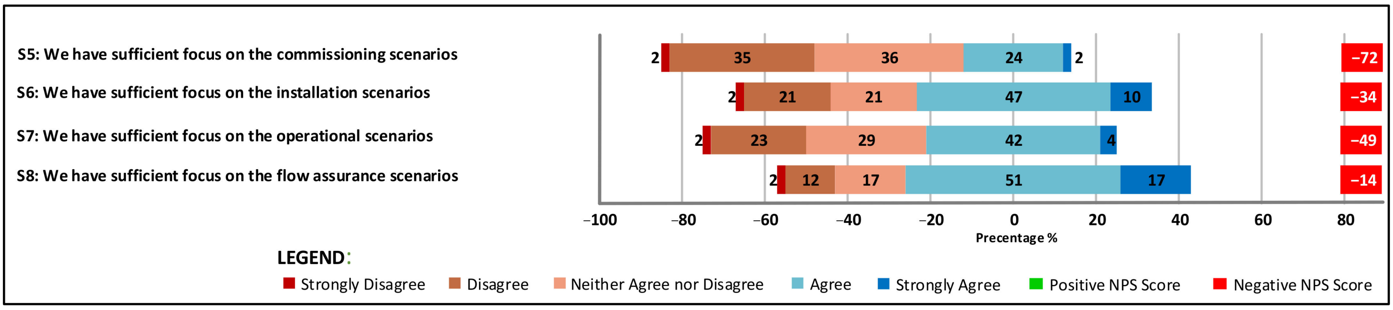

Figure 6. Survey results—operational scenarios.

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).

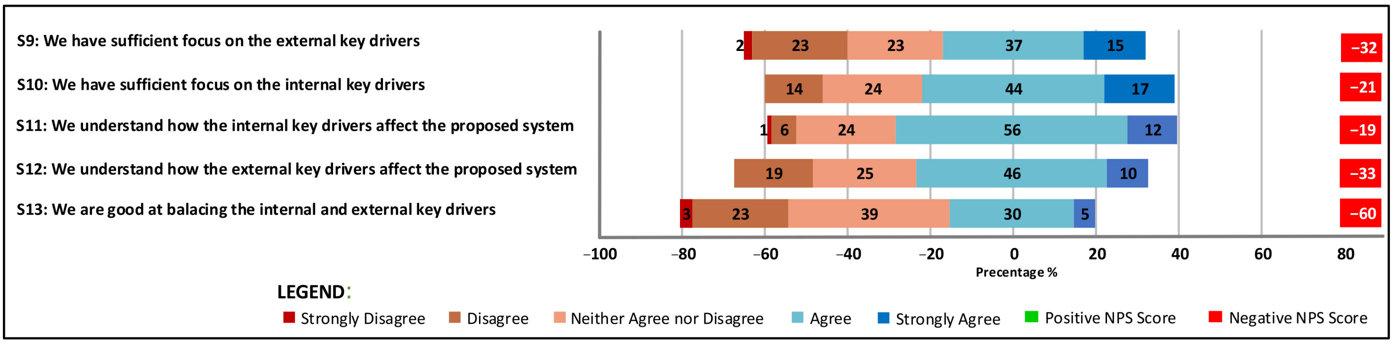

Figure 7. Survey results—key driver awareness.

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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