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Exploration and early validation in Systems Engineering

A study on combining systems and design practices in systems development towards innovations in Norwegian high-tech industries

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Dedication

To my children; Mia, Theo, and Levi.

I hope one day you will read this thesis and let it inspire you.

You have certainly inspired me.

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Marianne Kjørstad

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Abstract

This thesis on exploration and early validation in Systems Engineering focuses on engineering practices towards high-tech innovations in the early systems development phase. It looks towards systems and design approaches to characterize and employ a framework supporting systems engineers in defining the problem to be addressed and the iterative creation of systems concepts to resolve these issues.

The evolving technology enables systems that interact and intervene with people and organizations more complexly than ever before. Consequently, the high-tech industry faces a rapidly changing market need and systems with increasing socio-technical complexity. The industry needs rapid adaptation to change to stay competitive. Staying ahead of competitors and providing significant innovative solutions are essential for the industries' business value. In recent years, the literature has proposed combining systems and design approaches to cope with real-world problems in systems development towards innovations. However, the literature on practices to support this combination is still young. As a result, there is a knowledge gap of a practical framework to achieve this.

This thesis presents research conducted as part of a research collaboration project with four Norwegian high-tech companies and two academic partners within Systems Engineering and Systems Oriented Design. The research collaboration project aimed to establish a combined systems and design framework for the industry partners to achieve significant innovations. The industry context of this thesis is within the business domains of the four industry partners, primarily focusing on the early systems development of a large-scale renewable energy system for operation in ocean space. This thesis also includes results from researching engineering practices in early systems development of product innovations in land-based industries such as chemical and demolishing plants.

The thesis is article-based and consists of four independent and interlinked studies using mainly qualitative research methods. The four appended articles present the four studies. Articles 1 and 2 are part of an initial explorative study to clarify research goals and questions and gain insight into engineering practices and challenges through two industry cases. Article 3 analyzes ten industry cases exploring engineering practices from systems and design approaches and identifies industry needs and success criteria for a combined framework. Furthermore, Article 4 builds on the findings from Article 3 and employs the success criteria in a 2-year longitudinal industry case to synthesize a practical method. Finally, Article 4 evaluates the method in an industrial setting to gain insight into the main challenges in applying this way of working and provide a basis for further research.

This thesis contributes to the Systems Engineering body of knowledge by gaining insight into the industry needs for a combined systems and design framework in the early systems development phase. The thesis identifies the characteristics of a framework and broadens the theoretical understanding of how such a framework supports the engineering practices towards high-tech innovation. Furthermore, the thesis proposes a practical method to guide the systems engineers in employing the framework and indicates potential challenges and lack of system engineers' skills to practice this way of working.

Keywords: Systems Engineering, Systems Architecting, systems development, early validation, innovation, socio-technical systems, creative problem-solving

List of Articles

Article 1

Kjørstad M., Falk K., Muller G., Pinto J. (2019). Early Validation of User Needs in Concept Development: A Case Study in an Innovation-Oriented Consultancy. In: Ahram T, Karwowski W, Taiar R, eds. Human Systems Engineering and Design. IHSED 2018. Advances in Intelligent Systems and Computing, vol 876. Springer, Cham, 54-60. doi: 10.1007/978-3-030-02053-8_9

Article 2

Kjørstad, M., Mansouri, M., Muller, G., Kjenner, S. (2019). Systems Thinking for Early Validation of User Needs in the Front End of Innovation; a Case Study in an Offshore SoS. Systems of Systems Engineering Conference SOSE 2019. doi: 10.1109/SYSOSE.2019.8753865

Article 3

Kjørstad M., Falk K., Muller G. (2020). Exploring a Co-Creative Problem Solving Toolbox in the Context of Norwegian High-Tech Industry. IEEE Systems Journal. doi:10.1109/JSYST.2020.3020155

Article 4

Kjørstad, M., Muller, G., Falk, K. (2021). Co-Creative Problem Solving to Support Rapid Learning of Systems Knowledge towards High-Tech Innovations: A Longitudinal Case Study. MDPI Systems Journal, 9(2):42. doi: 10.3390/systems9020042

Supporting Articles

Guntveit, M., Kjørstad, M., Sevaldson, B. (2020), Early Validation of Stakeholder Needs by Applying Co-creation Sessions. INCOSE International Symposium 2020, 30(1), 1387-1404. doi: 10.1002/j.2334-5837.2020.00793.x

Vanebo, R., Kjørstad, M. (2020), An Interactive Tool for Collaboration and Knowledge Sharing of Customer Needs in the Conceptual Phase. INCOSE International Symposium 2020, 30(1), 902-919. doi: 10.1002/j.2334-5837.2020.00762.x

Pinto, J., Falk, K., Kjørstad, M. (2019), Inclusion of human values in the specification of systems: bridging design and systems engineering. INCOSE International Symposium 2019, 29(1), 294-300. doi: 10.1002/j.2334-5837.2019.00604.x

Sjøkvist, N., Kjørstad, M. (2019). Eliciting Human Values by Applying Design Thinking Techniques in Systems Engineering. INCOSE International Symposium 2019, 29(1), 478-499. doi: 10.1002/j.2334-5837.2019.00615.x

Muller, G., Falk, K., Kjørstad, M. (2019). Systemic Innovation Toolset in Evolving Toolbox for Complex Project Management, Ed. Gorod, A., Hallo, L., Ireland, V., Gunavan, I., Auerbach Publications. doi: 10.1201/9780429197079

Additional Articles

Kjørstad, M., Falk. K. (2018), A Systems Engineering Assessment of Emergency Disconnect System from the User Perspective. INCOSE International Symposium 2018, 28(1), 1078-1092. doi: 10.1002/j.2334-5837.2018.00535.x

Imset, M., Falk K., Kjørstad M., Nazir S. (2018) The Level of Automation in Emergency Quick Disconnect Decision Making. Journal of Marine Science and Engineering, 6(1):17. doi: 10.3390/jmse6010017Dedication

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1 Introduction

This thesis on exploration and early validation in Systems Engineering focuses on engineering practices towards high-tech innovations in the early systems development phase. It looks towards systems and design approaches to characterize and employ a framework supporting systems engineers in defining the problem to be addressed and the iterative creation of systems concepts to resolve these issues.

This chapter introduces the background, research context, and knowledge gaps to clarify the relevance and intended contribution of the thesis. Furthermore, it presents the research goals and questions and a brief outline.

1.1 Background

The evolving technology enables systems that interact and intervene with people and organizations more complexly than ever before. Consequently, the high-tech industry faces a rapidly changing market need and increasing socio-technical complexity in systems development.

In high-cost countries like Norway, the industry needs rapid adaptation to changes to stay competitive. Therefore, staying ahead of competitors and providing significant innovative solutions are essential for their business value. This thesis defines significant innovations as *"solutions beyond the ordinary."* The inspiration for this terminology is the Boderc research project conducted through the Embedded Systems Institute in Eindhoven, Netherlands (M. Heemels & Muller, 2006). Mature companies often rely on incremental innovation and consolidation to grow, while significant innovations are harder to achieve (Muller, 2018a; Tverlid, 2020).

In the early phase of systems development, the knowledge about the system over its lifecycle is typically low, while the degree of design impact is high. Systems Engineering (Walden, Roedler, Forsberg, Hamelin, & Shortell, 2015) has proven to be an effective approach for developing technical (hard) systems. However, Checkland (1999, p. A35) described the *"failure of Systems Engineering"* and the development of the Soft Systems

Methodology (SSM) in the early 70s. He claimed that Systems Engineering lacks the focus on soft aspects to cope with socio-technical complexity. Soft Systems Thinking has proven valuable in addressing real-world problems and creating innovations (Checkland, 1999; Donaldson, 2017; Jackson, 2019). The focus on soft systems has increased in Systems Engineering, and INCOSE's latest definition of Systems Engineering embraces the soft aspects as part of the Systems Engineering practices (H. Sillitto et al., 2019).

A combined systems and design approach is assumed to support better the early systems development phase towards significant innovations than current Systems Engineering practices (Donaldson, 2017; Shafaat & Kenley, 2015; Tomita, Watanabe, Shirasaka, & Maeno, 2017; Wade, Hoffenson, & Gerardo, 2017; Watanabe, Tomita, Ishibashi, Ioki, & Shirasaka, 2017; White, 2016). Design fields such as Participatory Design and contemporary Design Thinking often emphasize the importance of exploration and early validation to provide innovative solutions using collaborative and creative practices (Brown, 2008; Brown & Katz, 2009; Dorst, 2011; Gardien, Rincker, & Deckers, 2014; E. B.-N. Sanders & Stappers, 2008; E. B. Sanders, 2005; Tschimmel, 2012). Such practices are traditionally stronger in design approaches than in Systems Engineering.

Looking towards Systems Architecting, we find that Maier and Rechtin (2009) described a great systems architect as skilled as an engineer and as creative as an artist. Systems Architecting is an analytic, inventive, and creative process that thoroughly understands the problem and solution space and develops suitable architectures (H. G. Sillitto, 2009). Thus, Systems Architecting, as viewed by Sillitto (2009), presents a systems approach that can supplement Systems Engineering practices to innovate in the context of soft systems. Thus, this thesis focuses on combining systems and design practices from Systems Thinking, Systems Architecting, Systems Oriented Design, Participatory Design, and Design Thinking to support Systems Engineering practices in the early phase of systems development towards high-tech innovations.

1.2 Research Context

This thesis has primarily applied action research (Checkland & Holwell, 1998) through a three-year Norwegian research collaboration project with four high-tech industry partners and two academic partners. The partners' vision was to establish a Human Systems Engineering Framework (H-SEIF) to improve their engineering practices towards innovations by bridging Design Thinking and Systems Engineering. Thus, this thesis has focused on combining systems and design approaches to support Systems Engineering practices towards high-tech innovations.

The Norwegian Government and partners funded the project through RFF Oslofjordfondet under Grant ES583290. Semcon Norway, Ulstein Design & Solutions, TechnipFMC, and Kongsberg Innovation are industry partners. The academic partners are the University of South-Eastern Norway and The Oslo School of Architecture and Design within Systems Engineering and Systems Oriented Design.

The industrial context of this thesis is within the business domains of the four industry partners, primarily focusing on an in-depth industry case doing complex system of systems innovations for operation in ocean space. The thesis also includes inspiration from industry cases doing specific product innovations in land-based industries such as chemical and demolishing plants. All four industry partners are Norwegian high-tech companies focusing on strengthening their business value through significant innovations. The companies develop or contribute to developing complex systems to demanding environments, such as ocean space. Table 1 shows the profiles of the industry partners with regards to domain and size, followed by a brief introduction of each of the partners reflecting their maturity and business domain.

Table 1. Profiles of the four industry partners

Company	Domain	Employees (2019)
Semcon Norway	Innovation consultancy	80
Ulstein Design & Solutions	Ship design	50
TechnipFMC	Subsea EPCI supplier	1200[1]
Kongsberg Innovation	Innovation incubator	10

[1] Number of employees working in the Norwegian part of the company concerning this research.

Semcon Norway is an innovation consultancy. They shifted from a traditional engineering consultancy into an innovation consultancy during the past decade, focusing on product development based on human behavior. As a result, they have built up expertise in Design Thinking and Systems Engineering.

Ulstein Design & Solutions is a family-owned company with about 100 years of history designing and building ships, such as service operations and anchor handling vessels. They are well known for providing innovative solutions and have recently expanded into new markets such as expedition vessels. In recent years, they had a strong focus on strengthening their expertise in Systems Engineering.

TechnipFMC is an Engineering, Procurement, Construction, and Installation (EPCI) supplier of subsea systems and services with about 40 years of experience supplying reliable systems operating in a harsh environment. The EPCI supplier is skilled in engineering. In the last decade, it has strengthened its Systems Engineering expertise focusing on effective execution.

Kongsberg Innovation is an innovation incubator, providing services for the last 17 years to small-sized and medium-sized enterprises and start-ups developing innovative high-tech solutions. They have a solid connection to several medium-sized to large-sized high-tech companies, providing the advantage of these connections to their customers. The incubator focuses on value proposition and business models using tools such as the Business Model Canvas (Osterwalder, Pigneur, Clark, & Smith, 2010) towards the start-ups.

1.3 Knowledge Gaps

Although the literature identifies combined systems and design approaches as essential in systems development towards high-tech innovations, the literature on Systems Engineering practices to achieve this is still young. The literature proposes a combined approach to support exploration and early validation in the early phase of systems development. However, we do not yet know the main industry needs for a combined approach and how to best guide systems engineers to employ such an approach to support their needs.

When studying engineering practices in mature high-tech industries, this research found industries lacking practices to cope with complex problems in the early systems development towards high-tech innovations (Kjørstad, Mansouri, Muller, & Kjenner, 2019). Complex problems are a typical challenge in systems development towards high-tech innovations. Mature companies tend to focus on cost and innovation efficiency rather than significant innovation (Christensen, 2015; Christensen, Bartman, & Van Bever, 2016). Such companies may typically strive for key performance parameters such as high-quality products and engineering excellence, leaving little room for exploring innovative concepts and rapid learning through early failures. Systems engineers accustomed to such practices put their time and effort into developing high-quality concepts without early validation. Consequently, the learning process slows down as they lack practices to explore and early validate innovative solutions to complex problems.

Furthermore, when studying engineering practices in innovative industries, this research found industries evolving tacit knowledge on best practices to explore and early validate innovative concepts using Co-Creation (Kjørstad, Falk, Muller, & Pinto, 2019). Co-Creation is a practice typically applied in design approaches, such as Participatory Design, and focuses on collective creativity between designers and stakeholders (Jones, 2019; Micheli, Wilner, Bhatti, Mura, & Beverland, 2019; Ramaswamy & Ozcan, 2018; E. B.-N. Sanders & Stappers, 2008; Trischler, Pervan, Kelly, & Scott, 2018). Kjørstad, Falk, Muller & Pinto (2019) found problem and solution exploration as the central core of Co-Creation Sessions as practiced at one of the industry partners. The value of Co-Creation in Systems Engineering is less explored and may provide collaborative and creative practices supporting exploration and early validation in a combined systems and design approach.

Design approaches typically emphasize the importance of exploration and rapid learning for innovation (Brown, 2008; Brown & Katz, 2009; Dorst, 2011; Gardien et al., 2014; E. B.-N. Sanders & Stappers, 2008; E. B. Sanders, 2005; Tschimmel, 2012) and collaborative and creative practices are recognized to support problem exploration towards innovations (Bono, 2016; Daly, Yilmaz, Christian, Seifert, & Gonzalez, 2012; Dorst, 2019; Dorst & Cross, 2001; McFadzean, 1998, 2000; Murray, Studer, Daly, McKilligan, & Seifert, 2019). On the other hand, Systems approaches do not overlook the role of collaboration and creativity for innovation.

For example, INCOSE's recent definition of Systems Engineering includes the following definition of engineering; *"the action of working artfully to bring something about."* (H. Sillitto et al., 2019) and thus embraces art into the engineering process. Pugh (1981, 1990) described the need for collaboration and creativity during concept selection using the famous *"Pugh matrix"* as early as the 1980ties. Furthermore, Maier & Rechtin (2009) described a great systems architect as skilled as an engineer and creative as an artist in their book named *"The art of Systems Architecting."* Sillito (2009) highlighted creativity and collaboration as essential skills for the Systems Architect to understand and communicate systems behavior to successfully bring forward systems fit for purpose.

Tacit knowledge on systems and design practices to support exploration and early validation towards innovation in the industry is growing. However, the systems engineers need guidance in how and when to best use such practices. There are knowledge gaps on employing such practices into a practical framework for systems development towards high-tech innovations. These knowledge gaps lead to the research problem of the lack of a practical framework combining systems and design practices in Systems Engineering. Thus, this thesis builds on the research collaboration project's vision of establishing a H-SEIF (framework).

1.4 Research Goals and Questions

Based on the identified knowledge gaps, the main goal of this research is threefold. This research aims to:

1. Explore and understand the industry needs for a framework combining systems and design practices in the early systems development phase
2. Broaden our theoretical understanding of how such a framework may support Systems Engineering practices towards high-tech innovations
3. Provide results that may guide systems engineers in best practices for combining systems and design practices that fit their industry context

In the first part of this research, we conducted an exploratory study for research clarification and identified three main research questions to reach the research goal. The main research questions were split into sub-questions as the research progressed. Articles 1 and 2 describe results from the exploratory study, while Articles 3 and 4 answers the research questions.

RQ1: *What are the desired characteristics of a combined systems and design framework supporting systems engineers in the early systems development phase?*

To answer RQ1, we identified industry needs from the learnings in the explorative study and conducted participatory research approaches to gain further insights into the industry partner's challenges and potential solutions. First, we researched ten industry cases as a joint effort between researchers in the research collaboration project. After that, we analyzed how the engineering practices supported the industry needs and outlined a combined framework. Article 3 answers the following sub-questions:

a) What are the industry partners' needs for a combined framework?
b) How do the explored engineering practices support the industry partners' needs?
c) What may be the outline of a framework?

RQ2: *How can systems engineers employ such a framework in a context of socio-technical complexity?*

To answer RQ2, we conducted action research in a longitudinal industry case at the EPCI supplier over two years to synthesize a method to employ the framework. First, we conducted sessions in the industry case employing success criteria identified in Article 3. After that, we synthesized the learnings into a practical method to support the systems engineers in the industry case. The first part of Article 4 answers the following sub-questions:

a) How can the framework support systems engineers at the EPCI supplier in rapid learning and early validation?

b) How may the systems engineers at the EPCI supplier employ the framework using a practical method?

RQ3: *What may be the main challenges for systems engineers to employ such a framework?*

To answer RQ3, we evaluated the proposed method in the industry case at the EPCI supplier. We also approached the industry partners to gain insight into the method's context dependencies. The second part of Article 4 describes the results from the evaluation, while Section 4.4.3 describes the results from interviewing representatives from the industry partners. Thus, the second part of Article 4 answers the sub-question:

a) What may be the main challenges for the systems engineers at the EPCI supplier to apply the method?

Furthermore, Section 4.4.3 answers the sub-question:

b) How can the method support systems engineers at the other industry partners?

Figure 1 illustrates how the appended articles support the main research questions and relates the research context to each article. Articles 1 and 2 describe results from the context of the innovation consultancy and the EPCI supplier. Article 3 describes results from the context of all four industry partners, while Article 4 describes results from the context of the EPCI supplier.

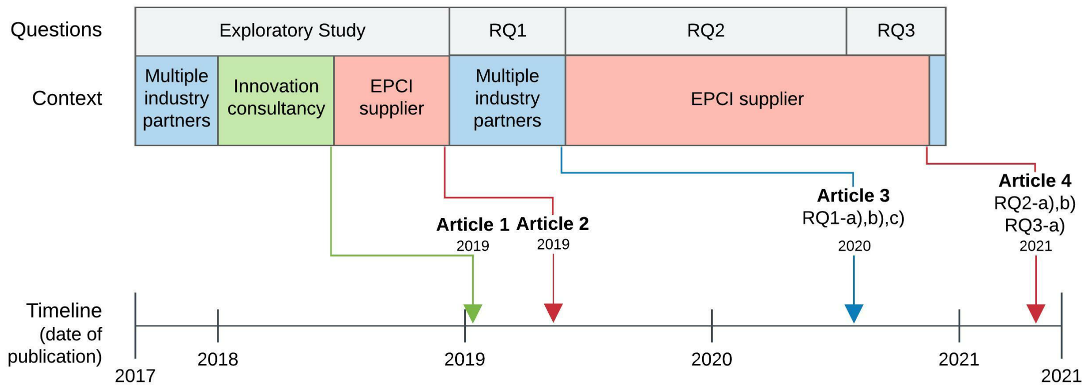

Figure 1. Relating the research questions to the appended articles and research context

1.5 Thesis Structure

This thesis consists of six chapters, and this chapter (**Chapter 1**) introduces the purpose and relevance of the thesis, its goal, and its intended contribution.

Chapter 2 provides the frame of reference for the thesis and positions the thesis within the relevant theory.

After that, **Chapter 3** describes the research approach applied in the thesis and the rationale for the chosen approach. The end of the chapter provides the approach to the validation of research results.

Chapter 4 presents and discusses the main results in the four appended articles with references to the theoretical frame in Chapter 2. This chapter presents the results in four sections, one for each article.

Chapter 5 discusses the validity of the research results, using the approach to validation in Section 3.5.

Finally, **Chapter 6** concludes the thesis by answering the research questions in Section 1.4, describing its main contributions, limitations, and recommendations for further research.

2 Frame of Reference

This chapter clarifies terms, describes the research relevance and positions the thesis within its theoretical frame. This chapter reprints selected literature from the appended articles and other work made as part of this thesis. Figure 2 shows the relation between the sections in this chapter.

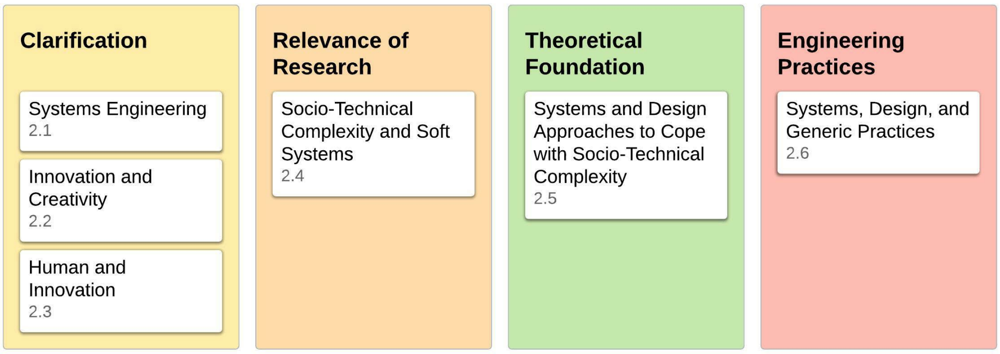

Figure 2. Relations between the sections in Chapter 2 Frame of Reference

Firstly, the initial explorative study identified the need to define Systems Engineering, Innovation, and Human as elements of the envisioned H-SEIF (framework). Section 2.1, 2.2, and 2.3 define the terms (clarification).

Secondly, exploring engineering practices at the industry partners identified challenges in achieving significant innovations in a socio-technical context. Furthermore, the industrial exploration provided insight into how a combined systems and design approach could support the challenges. Section 2.4 reviews literature on the challenges (relevance), while Section 2.5 reviews the literature on systems and design approaches assumed to cope with socio-technical complexity (theoretical foundation).

Finally, Section 2.6 presents the literature review conducted while exploring engineering practices in industry cases to identify the framework's characteristics and synthesize a practical method to support this way of working (engineering practices).

2.1 Systems Engineering

This thesis defines Systems Engineering according to The International Council of Systems Engineering (INCOSE). INCOSE was formed in 1990 and is the accepted organization for researchers and practitioners within Systems Engineering. They define Systems Engineering as follow:

"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." (H. Sillitto et al., 2019)

A systems engineer is a person practicing Systems Engineering. However, a systems engineer goes by many different names in the industry, such as product developer, product engineer, or systems architect, to mention a few (Beihoff et al., 2014). Many perceive Systems Engineering as a young discipline. Research on Systems Engineering is hence even younger.

2.2 Innovation and Creativity

There are numerous definitions of innovation in the literature and how innovation and creativity are interlinked (Mcadam & Mcclelland, 2002). This thesis looks towards psychological and organizational theory to define the role of *innovation* in the industry partners' envisioned H-SEIF (framework). We adhere to the definition of innovation provided by West & Farr (West & Farr, 1990) and the relation between innovation and creativity by Runco (Runco, 2014). West & Farr define innovation as follows:

"the intentional introduction and application within a job, work team or organization of ideas, processes, products or procedures which are new to that job, work team or organization and which are designed to benefit the job, the work team or the organization" (West & Farr, 1990, p. 9).

We add the term engineered systems to "*ideas, processes, products or procedures*" in the above definition by West & Farr to relate to Systems Engineering.

Innovation and creativity relate strongly to each other. Runco described the relation accordingly: "*one might say that innovation represents one application of creative thinking*" (Runco, 2014, p. 395). Runco further connected innovation to the need for originality with effectiveness, while creativity is stronger connected to originality with intrinsic motivation. He placed innovation on a continuum between originality and effectiveness and highlighted the need for a balance of those two. Runco separated innovation from routine problem-solving, as the latter has an even higher need for effectiveness and less need for originality.

Creating innovative solutions requires both organizations supporting collaborative and explorative ways of working, as well as multi-disciplinary project teams with the ability and willingness to do so (Koen et al., 2002; McFadzean, 2000; Nijstad, Berger-Selman, & De Dreu, 2014; Paulus & Brown, 2003; West, 2001; Wong, Tjosvold, & Liu, 2009). We split between *incremental and significant innovations*, the latter meaning *"solutions beyond the ordinary."* Mature organizations often rely on consolidation and incremental innovation to grow, while significant innovations are harder to create (Muller, 2018a; Tverlid, 2020). This thesis focuses on engineering practices supporting significant innovation rather than incremental innovation, thus supporting the industry partner's vision of a combined framework to strengthen their business value.

2.3 Human and Innovation

This thesis builds on Human Systems Integration in Systems Engineering, contemporary Design Thinking, and business theory to describe the role of *human* in the industry partners' envisioned H-SEIF (framework). Boy (2017) emphasized the importance of Human-Centered Design in Systems Engineering to cope with the current socio-technical evolution. Furthermore, Boy viewed Human Systems Integration as an enabler to integrate Human-Centered Design in Systems Engineering practices. INCOSE describes Human Systems Integration as follows:

"Human Systems Integration (HSI) is the transcultural and transdisciplinary technical and management process used to ensure that the human elements of a system are appropriately addressed and integrated within the wider systems engineering lifecycle and management approach to a project. HSI involves analyzing, designing and evaluating technological, organizational and human systems." (INCOSE HSI Working Group, 2021)

Looking towards contemporary Design Thinking and design-driven innovations, we find the founder of the Innovation Design Engineering Organization (IDEO) and the "*d.school*" at Stanford University, David Kelley. He highlighted the need for a creative mindset in innovation and the importance of empathy with users to meet the users' unmet needs (Kelley & Kelley, 2015). In business theory, strategies to achieve innovative businesses often refer to Porter's five forces (Porter, 2008) and Kotter's 8-step to accelerate change (Kotter, 2014). Michael Porter emphasized the importance of people and organizations for innovations, while John Kotter highlighted the importance of collaboration to achieve innovations.

Thus, the thesis describes the role of human in the H-SEIF as *collaborative and creative engineering practices to develop systems meeting the operational user need. Furthermore, these practices need to work for and with the people in the organization.* The engineering practices may require adaption to established engineering processes and current best practices in that organization. Thus, this thesis focuses on collaborative and creative engineering practices in systems development towards innovation that fit the industry partners' context.

2.4 Socio-Technical Complexity and Soft Systems

Systems Engineering (Walden et al., 2015) has proven to be an effective approach for developing technical (hard) systems. However, people, organizations, and technical functionality increase complexity in today's high-tech systems. Checkland (1993) described such socio-technical complexity as real-world problems and introduced soft systems to address this. Innovating in a context of soft systems using a Systems

Engineering approach has proven challenging (Checkland, 1999; Dove, Ring, & Tenorio, 2012; Jackson, 2006; Shafaat & Kenley, 2015; Tomita et al., 2017; Wade et al., 2017; Watanabe et al., 2017).

The focus on soft aspects to cope with socio-technical complexity is not that strong in Systems Engineering (Checkland, 1999; Donaldson, 2017; Jackson, 2019). Fields as Participatory Design and contemporary Design Thinking emphasize collective creativity with the purpose of innovation (Brown, 2008; Brown & Katz, 2009; Dorst, 2011; Gardien et al., 2014; E. B.-N. Sanders & Stappers, 2008; E. B. Sanders, 2005; Tschimmel, 2012). Recent literature proposed to look towards systems thinking and design processes to improve on this (Donaldson, 2017; Shafaat & Kenley, 2015; Tomita et al., 2017; Wade et al., 2017; Watanabe et al., 2017; White, 2016).

2.5 Combining Systems and Design Approaches

General Systems Theory developed by Bertalanffy in the 1940s has provided a good basis for a general system approach in recent literature (H. Sillitto et al., 2017). Bertalanffy (1972) described Systems Theory as a scientific approach to general understanding systems, from biological systems to conceptual systems. Gharajedaghi (2011) built on Systems Theory and characterized systems behavior using the five principles of openness, purposefulness, multidimensionality, emergent property, and counterintuitivity. To define problems and develop solutions, he emphasized the importance of viewing systems through these principles. He stated that "*no problem or solution is valid free of context*" (Gharajedaghi, 2011, p. 31). The importance of a Systems Thinking mindset in engineering to solve real-world problems is well documented in the literature (Checkland, 1993; Salado & Nilchiani, 2013; H. Sillitto et al., 2017).

The lack of soft consideration in Systems Engineering (Walden et al., 2015) has been a topic for decades. For example, Peter Checkland described the "*failure of systems engineering*" and the development of the Soft Systems Methodology (SSM) in the early 70s (Checkland, 1999, p. A35). Checkland emphasized the need to consider the political aspects of human activities to make changes in the real world that are both feasible and desirable. The leading developers of SSM are Checkland and Wilson. They have published a fair amount of literature on SSM and how it has evolved over the years (Checkland, 1993, 1994, 1999; Checkland & Poulter, 2006; Wilson & Haperen, 2015).

Jackson (2019) introduced Critical Systems Thinking that combines different systems approaches to cope with various forms of complexity. Jackson provided a thorough overview of primary systems approaches, including SSM. He described Systems Engineering as hard Systems Thinking and recognized Systems Engineering as a well-proven approach coping with technical complexity. However, he emphasized the need to look towards other systems approaches for considering various forms of complexity, such as process, structural, political, people, and organizational complexity. INCOSE's recent definition of Systems Engineering (H. Sillitto et al., 2019) supports the importance of soft systems thinking.

Looking towards Systems Architecting, we find that Maier & Rechtin (2009) described a great systems architect as skilled as an engineer and creative as an artist. Sillito (2009) emphasized the need for an analytic, inventive, and creative process in Systems Architecting to thoroughly understand the problem and solution space and create suitable architectures. He split between architecting and architectural modeling, both activities interacting and being part of creating a system fit for purpose. The main objective of the systems architect is to understand how the system behaves and effectively communicate this towards others (H. G. Sillitto, 2009). Muller (2011) proposed various informal methods (tools) for the systems architect to communicate systems behavior using a multi-view method. Muller emphasized the importance of multi-views in Systems Architecting to gain insight into multiple perspectives. A thorough understanding of stakeholder perspectives and needs is essential to design systems fit for purpose within a business context (2011).

Systems Architecting is not well accounted for within the literature on systems approaches. For example, Jackson (2019) did not mention Systems Architecting in his overview of major systems approaches. Furthermore, current literature lacks a unified definition of what Systems Architecting embraces as a systems approach and how to practice it. Emer, Bryan, Wilkinson, et al. (2011) found six different perspectives on Systems Architecting when interviewing systems architecting practitioners, including both informal and formal ways of working. The informal ways of working support reasoning about problems and solutions at a higher abstraction level, thus complementing formal architecting frameworks. From this view, informal ways of working in Systems Architecting present a systems approach that can supplement Systems Engineering in ways of working to innovate in a context of soft systems.

Wade, Hoffenson, and Gerardo (2017) discussed the strength and weaknesses of major systems and design approaches for designing complex systems. Their discussion included Design Thinking, Systems Thinking, Systemic Design, Engineering Design, and Systems Engineering. Wade et al. found Systems Engineering as weaker in the early phase of systems development than Systems Thinking, Design Thinking, and Systemic Design and proposed a unified approach combining the strengths of the primary approaches into a new Systemic Design Engineering. A pilot of such a curriculum combining elements from Systems Thinking, Design Thinking, and Systems Engineering in education has been taught at the Stevens Institute of Technology with promising results (Wade, Hoffenson, & Gerardo, 2019).

The need to explore a combined approach of Design Thinking and Systems Thinking into a new approach has been proposed by several (Donaldson, 2017; Shafaat & Kenley, 2015; Tomita et al., 2017; Wade et al., 2017; Watanabe et al., 2017; White, 2016). A combined systems and design approach is assumed to better cope with ill-defined problems in the early systems development phase to develop more innovative solutions. Rittel & Webber (1973) introduced wicked problems in the early 70ties to describe such ill-defined problems. Wicked problems are challenging problems with no optimal solutions and a focus area in design when developing societal systems. Such systems are overly complex and demand a different problem-solving approach than hard systems (Shafaat & Kenley, 2015; Tomita et al., 2017; Wade et al., 2017; Watanabe et al., 2017).

2.6 Systems, Design, and Generic Practices

This section presents the main literature reviews conducted while exploring engineering practices at the industry partners to characterize and employ a combined systems and design framework. The literature reviews were conducted to support each industry case's specific needs and include practices from Design Thinking, Participatory Design, Systems Architecting, Systems Thinking, Systems Engineering, Engineering, and general theory on creativity. Figure 3 shows the practices and their positioning in systems, design, and generic practices.

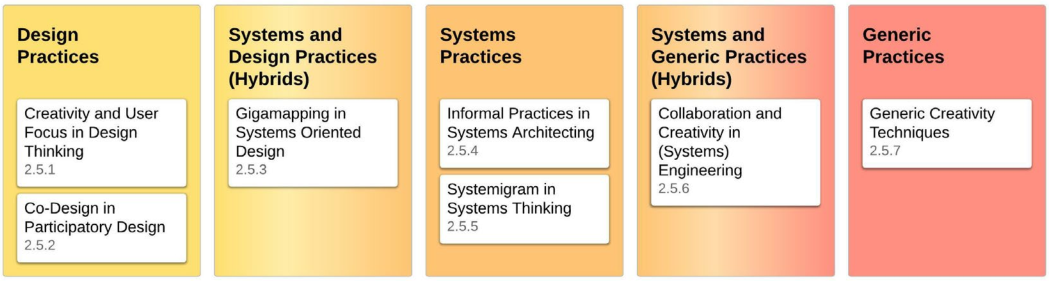

Figure 3. Systems, design, and generic practices supporting a combined systems and design framework

2.6.1 Creativity and User Focus in Design Thinking

Schön (1982) defined Design Thinking in the early 1980s, and others such as Rowe, Cross, Nelson, and Stolterman (Cross, 2006; Cross, Dorst, & Roozenburg, 1992; Nelson & Stolterman, 2012; Rowe, 1987) further theorized Design Thinking as a design approach. As practiced by the IDEO from the early 2000s, contemporary Design Thinking is viewed as the recipe for innovations by many. IDEO's founder, David Kelley (2015), highlighted a vital link between creativity and innovation and described creativity as a mindset that can be gained and used to find new solutions. Furthermore, IDEO advocates a creative mindset in a Human-Centered approach towards innovative solutions (Kelley & Kelley, 2015). Both in design and engineering to develop more desirable products and systems and in management and business aiming for more creative people and organizations (Brown & Katz, 2009).

Contemporary Design Thinking focuses on empathizing with users to create innovative products or services, providing a more extraordinary user experience (Lewrick, Link, & Leifer, 2018). Design Thinking offers processes and tools to support designers and multidisciplinary teams in creating innovations, such as the iterative Design Thinking Process Guide of the d.school at Stanford University (Plattner, 2010), including the steps; emphasize, define, ideate, prototype, and test. IDEO presents a similar model as the 3 Is; inspiration, ideation, implementation (Brown & Wyatt, 2010). Typical tools are rapid prototyping by building quick and dirty prototypes for early validation towards end-users and observing and engaging with end-users to gain insight into their unmet needs (Brown, 2008; Brown & Katz, 2009; Dorst, 2011; Gardien et al., 2014; Lewrick et al., 2018; Tschimmel, 2012).

As part of the research collaboration project, Pinto, Falk, and Kjørstad (2019) found inspiration in contemporary Design Thinking processes and proposed Visual Canvases as a visual tool to develop desirable, feasible, and viable systems. Visual canvases are structured templates using visualizations to emphasize with users and extract human values during stakeholder analysis. This way, it can be used for early validation of user needs in systems development.

2.6.2 Co-Design in Participatory Design

Björgvinsson, Ehn, and Hillgren (2000) discussed the Design Thinking approach by IDEO and claimed that this *"sounds like good old Participatory Design."* Participatory Design as a design practice and theoretical field originated from the 1970s. Co-Creation and Co-Design are typical terms used in Participatory Design. Sanders & Stappers (2008) described Co-Creation as collective creativity in any form. They further narrowed this term into Co-Design and described this as *"the creativity of designers and people not trained in design working together in the design development process."* Non-designers typically being users or customers (E. B. Sanders, 2005). Sanders et al. pointed to Participatory Design as a fitting approach in the front end of development. They claimed that Participatory Design will enable a better exploration, user- and context understanding in this fuzzy phase.

Co-Creation was coined by Prahalad and Ramaswamy in 2004 (Prahalad & Ramaswamy, 2004), focusing on the concept of Co-Creation between enterprises and consumers with the purpose of value creation and innovation (Akman, Plewa, & Conduit, 2019; Ramaswamy & Gouillart, 2010; Vargo, Akaka, & Wieland, 2020; Vargo & Lusch, 2017). Co-Creation or Co-Design in Participatory Design (E. B.-N. Sanders & Stappers, 2008) attends to stakeholder needs and systems operational context by the act of collective creativity between designers and other stakeholders, such as users or customers. Co-Creation focuses on treating customers and users as partners and emphasizes a participatory approach to developing new products or systems.

Sanders et al. (2008) positioned Participatory Design towards *"user as a partner"* and Human-Centered Design towards *"user as a subject"* focus. This positioning indicates a switch from the Design Thinking mindset towards a more collaborative approach. Sanders et al. pointed to Participatory Design as a fit approach in the front end of development. They claimed that Participatory Design would enable a better exploration, user, and context understanding in this fuzzy phase. Jones (2019) discussed various types of Co-Creation and identified possibilities for improving design Co-Creation methods. He highlighted the importance of continuity and investment in this way of working to provide insight into complex problems. Jones called for a systemic design framework to enable practitioners to select and modify the various Co-Creation methods.

2.6.3 Gigamapping in Systems Oriented Design

Systems Oriented Design (SOD) stems from Systemic Design that has evolved within the design community (AHO, 2014). This approach holds many similarities to conceptual modeling within Systems Architecting and SSM and provides a method to cope with complexity using visualization, called Gigamapping (Skjelten, 2014). Gigamapping is used to explore complex problems and interrelations by collectively drawing and writing on a large sheet of paper usually put on walls or tables. Gigamapping can be used to explore freely or more structured, such as using a timeline or canvas. Structured Gigamapping is typically to make a customer journey. Design practice using

Gigamapping has evolved as tacit knowledge, and the publications by Sevaldson and others (Sevaldson, 2011, 2013, 2018; Wettre, Sevaldson, & Dudani, 2019) have captured the tacit knowledge in recent years. Sevaldson (2018) highlighted the main benefit from Gigamapping to be sense sharing between stakeholders that Co-Create the Gigamap.

2.6.4 Informal Practices in Systems Architecting

As part of the systems architect's toolbox, Muller proposed the Illustrative Concept of Operations (ConOps) to gain insight into the system's operational scenarios (Muller, Falk, & Kjørstad, 2019; Solli & Muller, 2016). Systems Engineering (Walden et al., 2015) applies ConOps (Kossiakoff, Sweet, Seymour, & Biemer, 2011) and OpsCon (Wheatcraft, 2013) to describe the operational concept of a system using scenarios. Traditionally, ConOps and OpsCon are highly textual-based methods originating from the defense industry. Compared to the traditional ConOps, an Illustrative ConOps is a visual representation of the sequence of operation of the concept(s), usually captured in an A3. Illustrative ConOps can be used to validate concepts in communication towards stakeholders early. Solli and Muller (2016) applied illustrative ConOps in the Norwegian subsea industry. They found that illustrative ConOps resulted in prompt responses from systems engineers on various concepts and operations, expressing concerns and curiosity about the operational steps.

Muller (2018b) proposed Workshops as another tool in the systems architect's toolbox to support communication of systems behavior during systems development. Workshops enable cross-fertilizing and knowledge sharing during feasibility studies, design and specification, and system implementation. Muller proposed using time-boxing and multi-views in iteration to conduct effective workshops (Muller, 2009). Multi-views use a CAFCR (Muller, 2004) framework to view the system from multiple perspectives: the customer, application, functional, conceptual, and realization iteratively as the system mature. Time-boxing is to set an appropriate time box to achieve this within the duration of the workshop.

As part of the research collaboration project, Jensen, Muller, and Balfour (Jensen, Muller, & Balfour, 2019) found inspiration in Systems Architecting and proposed an Interactive Knowledge Architecture tool for knowledge sharing in the early phase of systems development. The Interactive Knowledge Architecture applies visualizations and interactive links to provide a usable and desirable interface for the systems engineers to share early phase concepts. Jensen et al. found the Interactive Knowledge Architecture to support knowledge transfer to customers and within development teams (Jensen et al., 2019).

2.6.5 Systemigram in Systems Thinking

Inspired by Checkland's (Checkland, 1993) way of visualizing systems, Boardman and Sauser developed a technique for visualizing *"readable"* systemic diagrams that capture concepts through Systems Thinking (Boardman & Sauser, 2008). They called this technique *Systemigram* and used it to communicate and confirm strategic intent. Boardman et al. described Systemigram as a complement to the richness of prose. Due to its easy readability, it would reach out to more people enabling a greater shared understanding. Blair, Boardman, and Sauser (2007) proposed using Systemigram as a storyboard for stakeholder communication. Cloutier, Sauser, Bone, and Taylor (2015) proposed using it for capturing knowledge about problems, while Squires, Pyster, Sauser et al. (2010) applied Systemigram to communicate a project's value proposition.

2.6.6 Collaboration and Creativity in (Systems) Engineering

The importance of collaboration and creativity for innovations is also supported in Systems Engineering and Engineering practices. Pugh (1981, 1990) highlighted the importance of group work and creativity in concept generation and evaluation (the Pugh matrix) as early as the 1980ties. Sage & Armstrong (2000) proposed collaborative and creative methods for systems synthesis, such as brainstorming (Osborn, 1953) and the morphological box approach (Zwicky, 1969). Lippert & Cloutier (2019) described the use of an extended TRIZ (Altshuller, 1984) to support systems engineers in creating innovations within digital Systems Engineering. White (2016) proposed a practical approach for Complex Adaptive Systems Engineering (CASE) to improve socio-technical Systems Engineering. His approach covered organizational and team aspects, such as the need for brainstorming and user experimentation. The CASE aimed to be an iterative and adaptive way of working for the team to operate on the *"edge of chaos"* (White, 2016, sec. 3.Y).

McFadzean (1998, 2000) supported the importance of creativity in engineering of innovative products or systems. McFadzean (1998) described techniques such as the present-future-opportunities, the change of perspectives, and wishful thinking. She called for a more vigorous use of creativity techniques in engineering and proposed a framework for creative problem-solving teams. The framework enables teams to select appropriate techniques based on their level of experience and need. McFadzean (2002a, 2002b) further elaborated the role of a neutral facilitator in such teams. The facilitator needs to address soft issues within the team to establish trust and deal with conflicts. She also described the effectiveness of such teams to depend on their experiences in using creative problem-solving techniques. According to McFadzean, some people may find creative problem-solving techniques uncomfortable. This discomfort can reduce the effectiveness of such techniques. In the worst case, people may not participate at all.

To support creative designs, Dorst and Cross (2001) described the importance of *co-evolving on the problem and solution space* by going back and forth on problem and solution exploration. They found the bridging between these two to support creative designs. To avoid fixation and jump to solutions, Daly, Yilmaz, Christian et al. (2012) found the generation of multiple concepts as crucial in the creation of innovations.

2.6.7 General Theory on Creativity

When we look towards the theory on creativity, there are several ways of stimulating creativity by changing a person's mindset. Well-known techniques for stimulating creativity are to perform ideation, brainstorming, and brainwriting. Ideation was described by Young (2003) in 1965, while Osborn introduced the famous brainstorming technique in the 1950s (Osborn, 1953). Silverstein, Samuel, & DeCarlo built on this and proposed the use of brainwriting (Silverstein, Samuel, & DeCarlo, 2012, Chapter 20). De Bono (2016) introduced the term *lateral thinking* and separated it from the more familiar way of thinking as he called vertical thinking. De Bono emphasized the importance of exploring the problem landscape thoroughly to gain insight instead of jumping to a solution. To achieve this, it means that sometimes one needs to move in a direction that does not make much sense then, however, making perfect sense in hindsight once gaining insight (eureka).

Osborn looked into ideation for organizational creativity and claimed the effectiveness of a group over an individual (Osborn, 1953). Paulus & Nijstad (2003) thoroughly discussed the pros and cons of group versus individual creativity. Previous research on individual brainstorming has shown to produce more ideas than in groups. However, Paulus et al. concluded that ideas produced by a group are innovative as long as the group setting is productive, including factors such as trust, attitude, and the number of participants (avoiding production blocking and cognitive interference). Furthermore, Paulus et al. (2003) proposed the usage of a facilitator and a leader to cope with unproductive team dynamics. The group should be diverse enough to provide knowledge on the subject, but not too diverse as this may cause misunderstandings and conflicts. A diverse group enables a change of perspective and stimulates activation of long-term memory, resulting in more innovative ideas. Paulus et al. also found positive effects of combining individual ideation with group ideation to avoid participants biasing each other’s opinions and ideas.

3 Research Approach

This chapter describes the research approach for the thesis and the rationale for the chosen approach. We primarily applied action research (Checkland & Holwell, 1998) to explore systems and design practices at the industry partners. Action research focuses on acquiring knowledge by entering a real-world situation to improve it. We also applied similar participatory approaches, such as Case Study (Yin, 2018) and Industry-as-Laboratory (Muller, 2013; Potts, 1993). The thesis applies *industry case* to describe the various research cases in the industry independent of the type of participatory research approach applied.

Firstly, the chapter describes the research design and its rationale, including data collection methods and analysis. After that, a description of data collection and processing, research ethics, research philosophy, and approach to theory development. Finally, the end of this chapter describes the approach to validation of the research results.

3.1 Research Design

The chosen research design in this thesis is based on the Design Research Methodology (DRM) by Blessing and Chakrabarti (2009) (Figure 4).

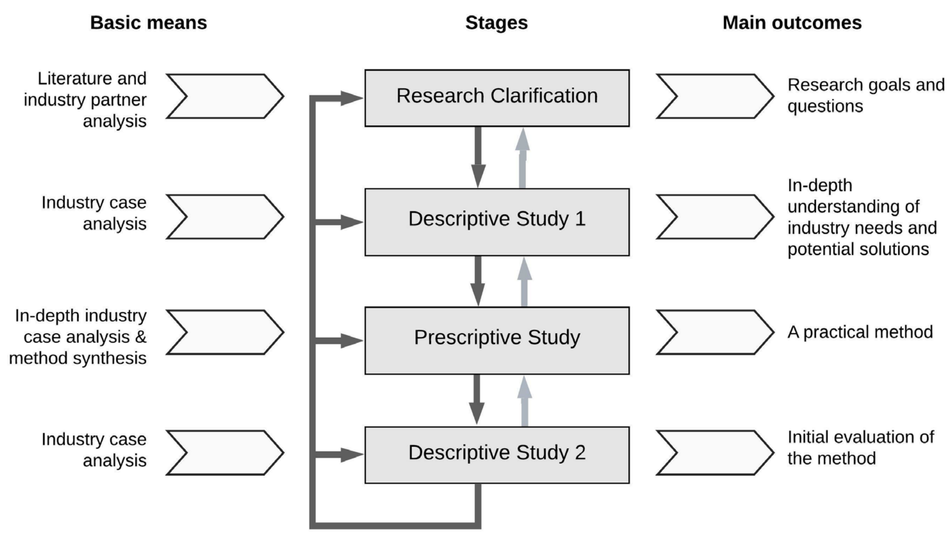

Figure 4. The research design illustrated using the DRM (adapted from Blessing et al. (2009, p. 15))

The DRM framework describes four research stages; Research Clarification, Descriptive Study 1, Prescriptive Study, and Descriptive Study 2. Figure 4 shows the four stages in the middle, the primary outcomes on the right, and the means on the left. The four research stages in the DRM aims to develop support in engineering and industrial *design research*. The way Blessing et al. define *design* holds many similarities to engineering:

"*those activities that actually generate and develop a product from a need, product idea or technology to the full documentation needed to realize the product and to fulfill the perceived needs of the user and other stakeholders*" (Blessing & Chakrabarti, 2009, sec. 1.1).

Thus, we found the DRM fit to explore industry needs for a combined framework and synthesize a practical method. The thesis adopts the DRM stage names; however, we applied a combination of prescriptive and descriptive studies in the second and third stages, as we found this approach suitable to understand the industry challenges and potential solutions in-depth.

Blessing et al. classified research projects with in-depth focus in one particular stage as highly suitable for Ph.D. projects, as they fit with the time and resources available in such studies (Blessing & Chakrabarti, 2009, sec. 2.3). For this research, we found it essential with an in-depth focus in the Descriptive Study 1 and the Prescriptive Study to understand industry needs and potential solutions and synthesize a practical method. An in-depth focus in the Descriptive Study 1 was achievable as a combined effort between the Ph.D. student and the other researchers in the H-SEIF project. Furthermore, we aimed for an initial Descriptive Study 2 to gain insights into challenges in practicing a combined systems and design framework and provide a basis for further research.

We continuously gained new knowledge and sharpened the research in each research stage, revisiting previous stages. For example, we revisited the Research Clarification stage and conducted literature analysis during industry case analysis in Article 3 and method synthesis in Article 4. The dark grey and light grey arrows in Figure 4 illustrate these iterations. As the research progressed, the research context changed between the industry partners. Figure 5 cross-references the research progress with the stages and questions and illustrates how the research context changed during the research. The subsequent subsections elaborate on the means and outcomes of each stage in light of the research context.

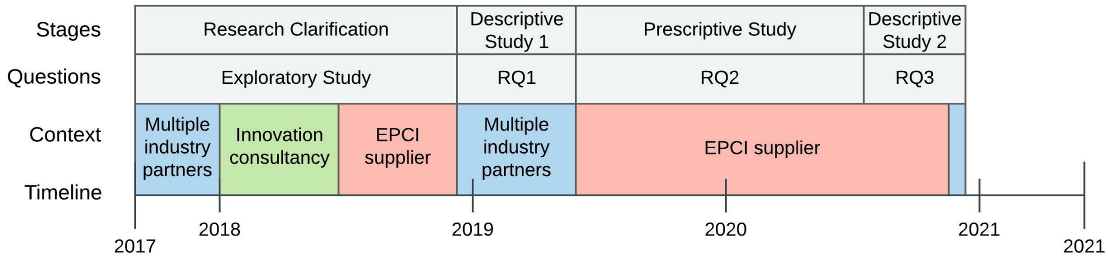

Figure 5. Cross-referencing research progress with research stages and questions

3.1.1 Research Clarification

The Research Clarification (the first stage of the research design in Figure 4) aimed to clarify the research goal and main questions. In this stage, we conducted informal interviews and focus groups with industry partners representatives over several months to understand the industry partner's needs (context in blue in Figure 5). Inspired by a similar previous research collaboration project on knowledge-based development, we developed a Customer-Interest A3 (Stenholm, Mathiesen, & Bergsjo, 2015) to explore the industry partners' needs. The partners evolved the content of the A3s in parallel with participating in focus groups and interviews. At the end of this period, we analyzed the A3s using coding (Creswell, 2014; Kaplan & Maxwell, 2005). We sharpened the research into three primary industry needs; 1) early validation, 2) exploring "*wow*" innovations, and 3) transfer of knowledge. We performed an initial literature analysis on the industry needs within Systems Engineering, Design Thinking, and Systems Architecting.

Furthermore, we explored engineering practices at two industry partners to gain a more in-depth understanding of the industry needs and potential solutions. Firstly, we conducted Case Study (Yin, 2018) to research the best practices for early validation of innovative concepts at the innovation consultancy. The context of the cases was product innovations in land-based industries such as chemical and demolishing plants. After that, we conducted Industry-as-Laboratory (Muller, 2013; Potts, 1993) in a development team at the EPCI supplier to gain insight into their best practices for systems development of innovative high-tech systems. The context of the industry case was an innovative large-scale renewable energy system (system of systems) to ocean space.

We reflected upon the differences in developing product innovations vs. large-scale system of systems innovations. The industry case at the EPCI supplier provided insight into the development team's lack of engineering practices supporting exploration and early validation in systems development towards innovations. At the same time, the industry case at the Innovation consultancy provided insight into their tacit knowledge in successfully applying systems and design practices in systems development of innovative products.

The main outcome of the Research Clarification was the research goals and main questions.

3.1.2 Descriptive Study 1

The Descriptive Study 1 (the second stage of the research design in Figure 4) aimed to identify characteristics of a combined systems and design framework in the context of the four industry partners. We explored systems and design practices through industry cases using participatory research approaches. Then, we analyzed how the practices supported the industry partners' needs identified in the Research Clarification. We conducted industry cases in development teams in the systems development phase of innovative products and services. These cases were a joint effort between researchers in the research collaboration project using participatory research approaches. In total, the research collaboration project explored five practices through ten industry cases that include the two industry cases conducted during the Research Clarification.

The partners in the research collaboration project chose practices fit for the context and need of each industry case as the research progressed. The innovation consultancy aimed to gain further insights into how the currently evolving practices at the company supported their needs. These practices were Visual Canvas (Pinto et al., 2019), Interactive Knowledge Architecture (Jensen et al., 2019), and Co-Creation Session (Kjørstad, Falk, et al., 2019). The academic partner within Systems Oriented Design introduced Gigamapping (Skjelten, 2014; Wettre et al., 2019) to all four industry partners as a potential new way of working to support their needs. The academic partner within Systems Engineering introduced Systemigram (Boardman & Sauser, 2008) and Illustrative ConOps (Muller et al., 2019; Solli & Muller, 2016) as potential solutions for the EPCI supplier.

Throughout the research project, the industry partners shared their experiences using the practices in half-yearly workshops. As a result, the ship designer and the EPCI supplier found inspiration to explore Interactive Knowledge Architecture as a new way of working at their companies. In addition, the innovation consultancy continued to research the usefulness of Co-Creation Sessions and Visual Maps to gain further insight into the value these practices could provide for their company.

Each of the industry cases had a time horizon of about three months. Table 2 shows the profiles of the industry cases. Master students researched six cases through master projects connected to the Systems Engineering program at the University of South-Eastern Norway. The industry partner employed four of these students during their master's education. The Ph.D. student was actively involved in these six cases and the leading researcher in the remaining four. The researchers formed the research design in the industry cases to fit the need and context for each case.

Table 2 refers to publications describing the chosen research design for each case. For example, Article 3 describes the results from Cases 1 and 6 while supporting articles and other articles published in the research context describe Cases 2-5 and 7-10. We primarily applied qualitative data collection methods in the industry cases, such as participant observations, formal and informal interviews, focus groups, and open-ended surveys. We combined qualitative and quantitative research methods in surveys using Likert scale statements (Likert, 1932) and found inspiration from Blessing et al. (2009) in the use of methods for data collection. During the design of formal interviews, we looked towards Kvale (2008) for support and inspiration.

Table 2. Profiles of the industry cases conducted in the Descriptive Study 1 (adapted from Article 3 © 2020 IEEE)

Industry case no.	Industry partner	Explored through	Method	References to publication
1	All	Ph.D. research	Gigamapping	Article 3
2	Innovation consultancy	Master project	Visual Canvas	(Pinto et al., 2019)
3	Innovation consultancy	Master project	Visual Canvas	(Sjøkvist & Kjørstad, 2019)
4	Innovation consultancy	Master project	Information Knowledge Architecture	(Jensen et al., 2019)
5	Ship designer	Master project	Information Knowledge Architecture	(Vanebo & Kjørstad, 2020)
6	EPCI supplier	Ph.D. research	Information Knowledge Architecture	Article 3
7	EPCI supplier	Ph.D. research	Systemigram	Article 2
8	EPCI supplier	Master project	Illustrative ConOps	(Aarsheim, Falk, & Kjenner, 2020)
9	Innovation consultancy	Ph.D. research	Co-Creation Session	Article 1
10	Innovation consultancy	Master project	Co-Creation Session	(Guntveit, Kjørstad, & Sevaldson, 2020)

As we explored industry cases, we gained insight into how the practices supported the industry needs and derived success criteria characterizing a combined framework. We surveyed the industry partners at one half-yearly workshop to verify the success criteria. The industry representatives responded to two statements in the survey; S1) perceived importance for a new method (the term "*new method*" relating to a new way of working for the partners), S2) satisfied by the current way of working. We designed the survey statements using the Likert scale (Likert, 1932) with the scale strongly disagree, disagree, neutral, agree, and strongly agree. We analyzed the survey results using a Net Promoter Scale (NPS) (Muller, 2013; Reichheld, 2003). Table 3 and Table 4, in Article 3, provide the profiles of the eight industry representatives and the NPS results, respectively.

The main outcome of Descriptive Study 1 was an in-depth understanding of the industry partner's need for a combined framework and potential solutions in the form of systems and design practices.

3.1.3 Prescriptive Study

The Prescriptive Study (the third stage of the research design in Figure 4) aimed to research how to employ the framework in the context of an in-depth industry case at the EPCI supplier. We applied action research (Checkland & Holwell, 1998) to employ the success criteria identified in the Descriptive Study 1 and continued researching the development team at the EPCI supplier. The team was in the systems development phase of a high-tech renewable energy system for ocean space. We actively engaged in daily meeting activities and supported the team in their daily tasks. As a result, we found the development team in specific need of support for exploration and early validation of innovative ideas and concepts in collaboration with internal stakeholders, such as business developers and subject-matter-experts.

The learnings from researching the innovation consultancy's best practices in the Research Clarification indicated to be a fit practice to support the development team at the EPCI supplier. Therefore, we adapted the innovation consultancy's best practices in applying Co-Creation Sessions to fit the context of the development team at the EPCI supplier and employ the success criteria. Guided by the success criteria, we planned and conducted sessions applying practices and techniques from systems, design, and generic practices that fit the team's specific needs and context of each session.

Table 3 provides an overview of the nine sessions conducted in the industry case. In Session 1, we observed the development team to gain insight into current engineering practices using sessions. We collected data during the planning of the sessions, during the sessions, and from the participants after the sessions using questionnaires and focus groups. The questionnaire included statements derived from the success criteria using a five-point Likert scale (Likert, 1932). The scale ranged from strongly disagree, disagree, neutral, agree, to strongly agree. The questionnaire also included open-ended questions for participants to report on benefits and concerns. The Likert scale responses were analyzed using a Net Promoter Score (NPS) (Muller, 2013; Reichheld, 2003). Article 2 provides the questionnaire results, including NPS.

Table 3. Profiles of the sessions conducted in the in-depth industry case in the Prescriptive Study (Article 4)

Session	Context	Participants	Methods for data collection
S1	Hazard identification analysis	6	Participant observation, questionnaire
S2	Technology qualification review	6	Participant observation, questionnaire
S3	Idea generation for research proposal	6	Participant observation, questionnaire
S4	Early concept exploration of the control design	6	Participant observation, questionnaire, informal interview
S5	Early phase review of the subsea storage design	6	Participant observation, questionnaire
S6	Idea generation early-phase pilot project	4	Participant observation, focus groups
S7	Lessons learned from a pilot project	5	Participant observation, focus groups
S8	Early phase review of water treatment design	5	Participant observation, focus groups
S9	Review of subsea storage design including installation	7	Participant observation, focus groups

We applied parts of the framework proposed by Midgley, Cavana, Brocklesby, et al. (2013) to analyze the sessions. Their framework's primary purpose was for evaluating systemic problem structuring methods. The framework focuses on *"the use of a particular method (or set of methods) in a context for particular purposes, giving rise to outcomes."* We split the session's *applicability* and *usability* to distinguish between factors impacted by the industry case (*context*) and the success criteria (*outcome*).

Applicability describes how well the session was conducted in the industry case, including planning and structure, while usability describes the session's ability to achieve the success criteria. Therefore, we categorized the notes into usability and applicability and used the success criteria to code (Saldaña, 2015) the notes on applicability. We identified three main capabilities and three impacting factors for successful sessions from analyzing the sessions. Finally, we integrated the learnings into a practical method to plan and conduct sessions in the context of the development team at the EPCI supplier.

The main outcome of the Prescriptive Study was the practical method to support the systems engineers in the development team at the EPCI supplier to achieve the capabilities.

3.1.4 Descriptive Study 2

The Descriptive Study 2 (the final stage of the research design in Figure 4) aimed to identify potential challenges for the systems engineers to apply the method in the context of the development team at the ECPI supplier. We passively observed the development team applying the method in two sessions, Sessions A and B. After the sessions, we conducted informal interviews with the facilitator and the problem owner. Table 4 shows the profiles of Sessions A and B.

Table 4. Profiles of the sessions conducted in the in-depth industry case in the Descriptive Study 2 (Article 4)

Session	Context	Participants	Methods for data collection
A	Prepare high-level visualization of a pilot project for external communication	5	Passive observation, informal interviews
B	Early review of subsea storage architectures	6	Passive observations, informal interviews

To gain further insight into how the method may support systems engineers in similar contexts, we approached representatives at the industry partners for feedback on how they perceived the value of such a method. We asked for feedback on what value the method could provide to their company and its usability in their context. We received feedback from two industry representatives at the innovation consultancy, one representative at the ship designer, and one at the EPCI supplier from a different business unit. The respondents were systems engineers and managers within Systems Engineering and Design.

The main outcome of Descriptive Study 2 was an initial evaluation of the proposed method in the development team at the EPCI supplier. Furthermore, this stage provided insights into how the ship designer, innovation consultancy, and another business unit at the EPCI supplier perceived the value of such as method applied at their companies.

3.2 Data Collection and Processing

We collected rich data from multiple contexts and perspectives throughout the research, such as notes from meetings, interviews, and surveys. We produced various artifacts based on this data for further analysis and synthesis. The artifacts served as a basis for internal and external presentations, discussions with industry and academic representatives, and writing up articles. Blessing et al. supported using such attributes to effectively structure the research (Blessing & Chakrabarti, 2009, Chapter 7.3).

Table 5 shows the main types of data collected during the research, and Table 6 shows an overview of the main types of produced artifacts.

Table 5. Main types of data collected during the research

Data	Format	Software/ Storage	Size
Notes from meetings, observations, discussions, reflections, informal interviews, focus groups	Research logbook	Evernote	About 100 pages / 35 000 words
Notes on findings in literature	Reference management system	Mendeley	About 700 items sorted in about 50 distinct folders
Industry partner input	Customer Interest A3s	Dropbox	One A3 per partner
Survey results, online	Online service	Nettskjema.no	11 distinct surveys, 41 respondents
Survey results, printed handouts	Scanned PDFs	Dropbox	30 respondents
Formal interview results	Recordings, transcriptions, connection keys	USN server	3 respondents
Various (pictures, documents, etc.)	Folder structure	Dropbox	3 GB

Table 6. Main types of artifacts produced during the research

Artifact	Format	Software	Size (slides/pages)
Research plan and progress	Visualization	MS PowerPoint	1
Line of reasoning	Presentation	MS PowerPoint	5
Research design	Visualization	MS PowerPoint	1
Industry partner analysis	Spreadsheet	MS Excel	1 (A3)
Industry case analysis	Presentation	MS PowerPoint	44
Success criteria synthesis	Presentation	MS PowerPoint	17
New method synthesis	Presentation	MS PowerPoint	17

The Norwegian Personal Data Act[1] and the General Data Protection Regulation (GDPR) regulated the processing of personal data in this research, and we processed personal data according to the guidelines given by the Norwegian Centre for Research Data (NSD)[2] and USN[3]. We strived to collect and store anonymous data throughout the research. We did not collect personal data from surveys, and we applied an approved online service to conduct the surveys. We gained written consent when recording interviews and stored the recordings according to the USN guidelines. The NSD assessed the data processing plan and found it per the regulations (reference no. 61185/3).

3.3 Research Ethics

The thesis followed the ethical research guidelines provided by the Norwegian National Research Ethics Committees[4]. Throughout the research, we strived to treat the people who participated in this research respectfully and to show research integrity through our work. Further, we strived to build and disseminate explicit and truthful scientific knowledge. We followed a recognized research methodology (Blessing & Chakrabarti, 2009) and academic guidelines for writing the research results (Blessing & Chakrabarti, 2009, Chapter 7.4). Before each scientific publication, the industry partners reviewed the articles for potential confidentiality issues. We made sure the subsequent updates of the articles did not affect the integrity of the research results.

3.4 Research Philosophy and Approach to Theory Development

We use Saunders, Lewis, and Thornhills' research onion to position the research philosophy and approach to theory development applied in this research (Saunders,

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

[2] https://nsd.no/personvernombud/en/index.html (the research was subject to notification)

[3] https://www.usn.no/om-usn/regelverk/ (specifically: processing personal data, processing audio recordings)

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

Lewis, & Thornhill, 2016). Figure 6 illustrates the research onion consisting of the many layers forming a research approach and position this research using red circles.

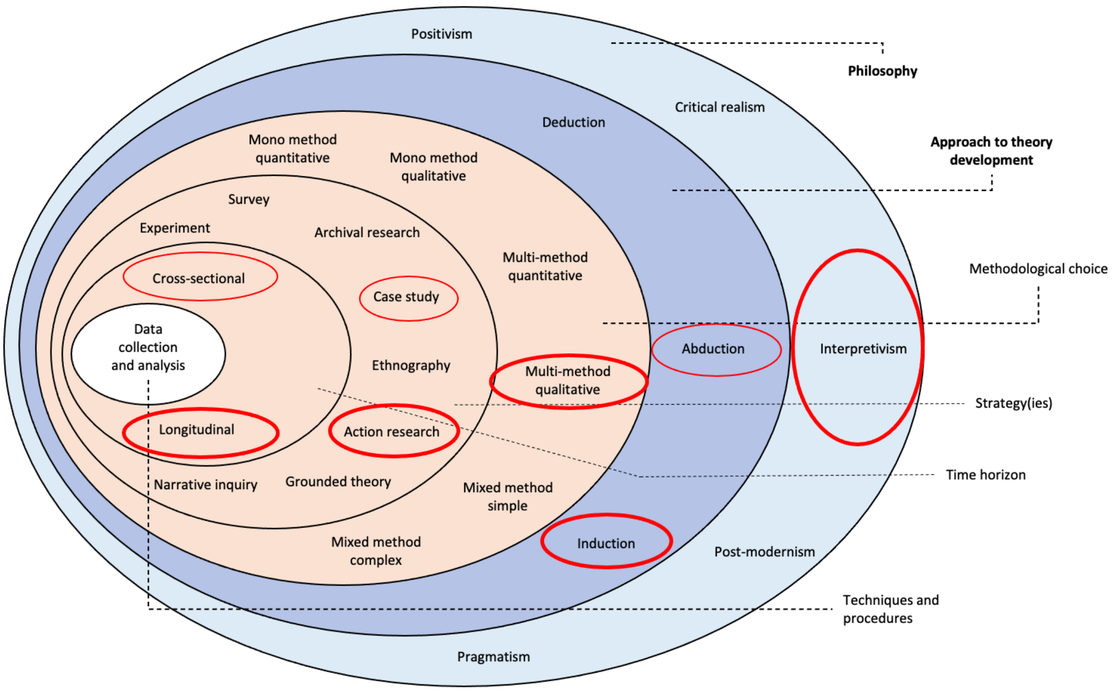

Figure 6. Positioning of the research approach in the Research Onion (adapted from Saunders et al. (2016, p. 124))

The outer layer shows the research philosophy, the middle layer shows the research design (methodology), and the inner layers show the research strategy and methods. The red circles' positions the research approach in this thesis in the onion. Thick lines illustrate a firmer positioning than thin lines. Sections 3.1 describes the research design and methods applied in this research. This section describes the two outer layers: an approach to theory development and philosophy.

The thesis primarily applied an inductive approach to theory development, using qualitative research methods. This approach allowed us to understand industry needs and potential solutions at the industry partners.

Firstly, we gained an in-depth understanding of needs and solutions within the industry partners through exploring systems and design practices. While the results were valuable to outline a framework, we needed to go further in-depth in a project team to develop and evaluate a method. Therefore, we gained a further in-depth understanding of needs and potential solutions in one project team at one of the industry partners. Sharpening the research from the industry partners to one industry case was essential to develop a practical method.

According to Reichertz (2013, p. 131), all scientific research includes three types of reasoning to build scientific knowledge; abduction, deduction, and induction. Reichertz described these as the following: "*Abduction searches for theories, deduction for predictions, induction for facts.*" (Reichertz, 2013, p. 131). Further, they argued that developing a theory using only one of the reasoning types provides little certainty and may lead to wrong conclusions.

Kaplan & Maxwell (2005) positions qualitative research in general within inductive reasoning. According to Kaplan et al., the value of qualitative research lies in gaining an in-depth understanding of the different perspectives and contexts of the study in a real life setting. We acknowledge that we applied diverse types of reasoning to various degrees throughout the research. However, we position the research primarily within inductive reasoning as we have sought a probable truth based on experiences from industry cases.

The research approach in the thesis leans towards an interpretivism philosophy. An interpretivism research philosophy is typical in qualitative social research (Robson, 2016). Interpretivism views the world as a construct of the interactions between people. Therefore, there are multiple realities based on individual perspectives. Interpretivism values subjective experiences to gain an in-depth understanding of the multiple perspectives in the world.

An interpretive view concurs well with our experiences in this research and underpins the action research strategy. The challenges engineers perceive during their daily work will vary from person, team, organization, and culture. To understand these challenges and potential solutions, one needs to actively engage with the engineers, taking on their language, rules, and behavior over a longer time horizon (Blessing & Chakrabarti, 2009, p. 259).

3.5 Approach to Validation of Research Results

In this thesis, we follow Maxwell's (2013) definition of the term validity to ensure trustworthiness in the research results. Maxwell defined validity as *"to refer to the correctness or credibility of a description, conclusion, explanation, interpretation, or other sorts of account."*

Maxwell (2013) proposed an eight-point checklist for testing the validity of qualitative research. The checklist tests the conclusion and the existence of potential threats to the conclusion and consists of the following eight points:

1. *Intensive, long-term involvement.* For example, using participant observations to gain more complete data from a research setting.
2. *Rich data.* Collecting data with a high degree of detail from multiple contexts.
3. *Respondent validation.* Using the research objects to verify that the researcher correctly interprets their feedback.
4. *Intervention.* Intervening with the research objects to gain further in-depth knowledge of the research setting.
5. *Searching for discrepant evidence and negative cases.* Taking into consideration the negative feedback and adjust the conclusion accordingly.
6. *Triangulation.* Gathering data from multiple persons and contexts using a variety of research methods.
7. *Numbers.* Quantifying qualitative findings to provide explicit arguments.
8. *Comparison,* such as comparing the same research setting at separate times or using literature or experience to compare with a specific research setting.

Further, Maxwell described two specific validity threats in qualitative research: bias and reactivity. We considered the checklist and researcher bias and reactivity while designing the research approach aiming for valid research results. Chapter 5 discusses the validity of the research results.

4 Results and Discussions

This chapter presents and discusses the main results in this thesis with references to the theoretical frame presented in Chapter 2. Furthermore, this chapter elaborates how the individual studies integrate and contribute to the research goals and questions presented in Section 1.4.

Figure 7 cross-references the research progress with articles and research stages. The figure applies colors to illustrate the link between the appended articles (above the timeline) and the corresponding research context that varied between the industry partners. The articles positioned below the timeline illustrate the supporting articles published in the research context, where most of the supporting articles are input to the industry case analysis in Article 3.

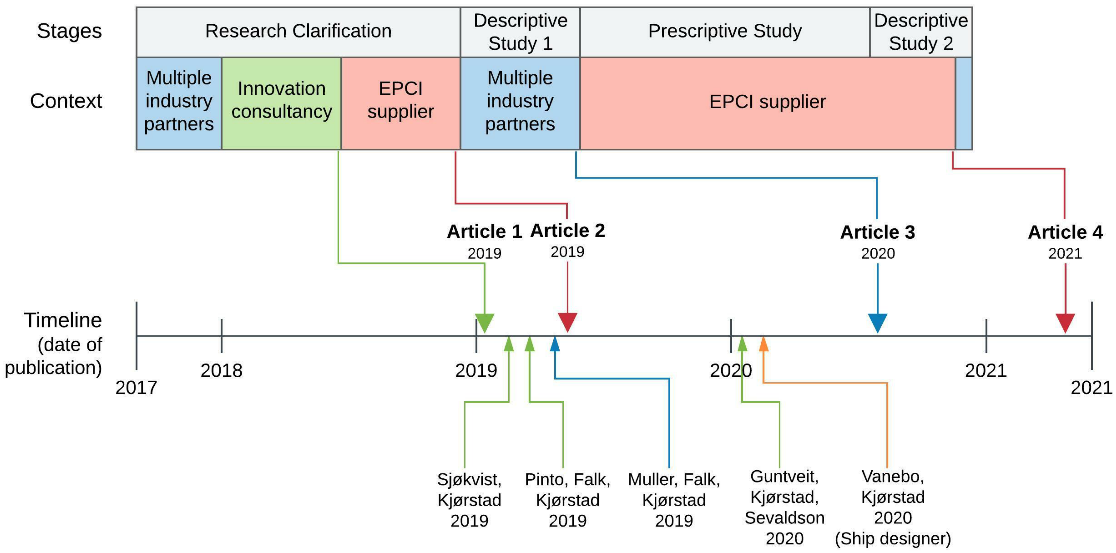

Figure 7. Cross-referencing research progress with research stages and articles

Articles 1 and 2 describe the results from exploring practices at the innovation consultancy and EPCI supplier during the Research Clarification phase. Article 3 describes the industry needs deriving from interviewing representatives from the four industry partners in the Research Clarification. Furthermore, Article 3 analyzes industry cases from the four industry partners in Descriptive Study 1. Article 4 splits into two parts and describes the results from the longitudinal industry case at the EPCI supplier in Prescriptive Study (Part 1) and Descriptive Study 2 (Part 2). Finally, Section 4.4.3 describes additional results from interviewing representatives from the industry partners in Descriptive Study 2 not included in Article 4.

4.1 Results and Discussions of Article 1

Title: Early Validation of User Needs in Concept Development; A Case Study in an Innovation-Oriented Consultancy.

Article 1 describes the results from applying Case Study (Yin, 2018) to research the innovation consultancy's best engineering practices in early systems development. The consultancy applied Co-Creation Sessions with customers and other stakeholders to explore and early validate innovative concepts. We actively observed the consultancy during three Co-Creation Sessions for three different customers for about three months. The industry context was product innovations in land-based industries such as chemical and demolishing plants. In addition, we conducted a literature review on early validation techniques and compared them to the innovation consultancy's best practices.

The innovation consultancy evolved its best practices using Co-Creation Sessions as an innovation service to customers over the last decade. The Co-Creation Sessions includes three phases (Figure 8); the insight phase prior to the session, the session, and the delivery phase after the session to synthesize the learnings and provide deliverables to the customer.

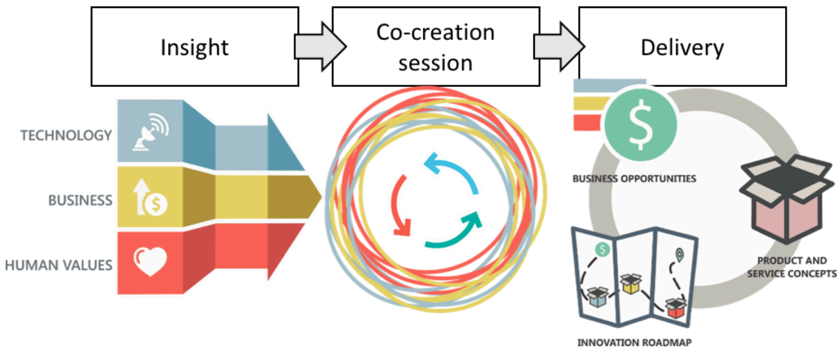

Figure 8. The three phases of Co-Creation Sessions as applied at the innovation consultancy (Article 1 © 2019 Springer)

We researched three Co-Creation sessions with three different customers at the consultancy. We analyzed the sessions using a key driver graph (W. P. M. H. Heemels et al., 2006) and derived three success criteria and ten means to achieve the criteria. Figure 9 presents the key driver graph as presented in Article 1 with the success criteria on the left side and the means to achieve the success criteria on the right side.

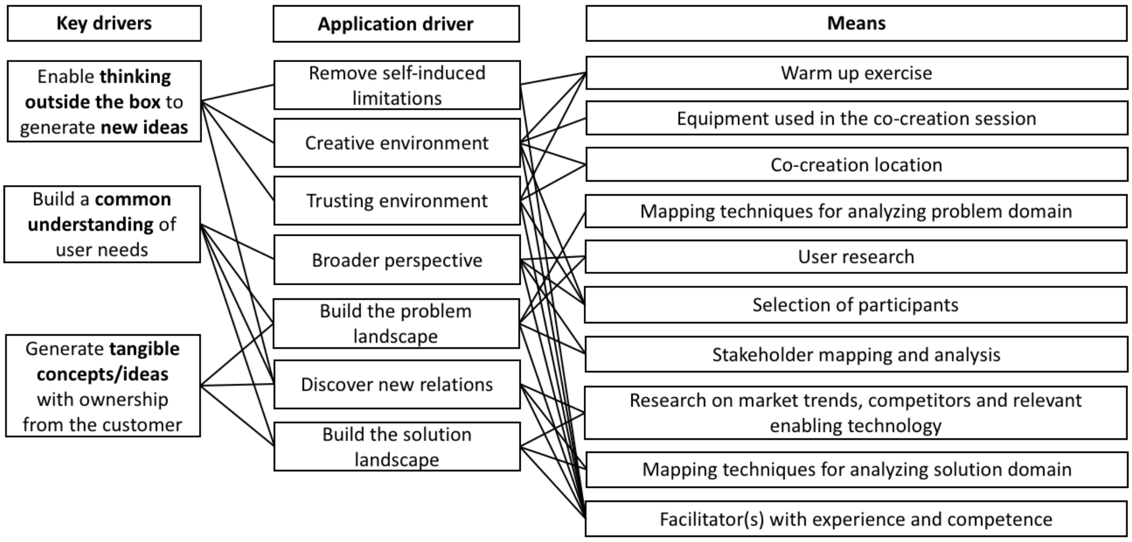

Figure 9. Key driver graph analyzing the innovation consultancy's best practice of Co-Creation with customers (Article 1 © 2019 Springer)

Article 1 found the three Co-Creation Sessions to be effective in exploration and early validation of user needs of innovative concepts. We derived criteria for successful sessions as the ability to *think outside the box to generate new ideas*, *build a shared understanding of user needs*, and *generate tangible concepts with ownership from the customer*. We identified the means to achieve this as research on user needs, technology and market trends, techniques used for analyzing the problem and solution domain, and selection of participants. Furthermore, we observed that the facilitator held experience and competence to guide the participants in achieving all three success criteria, thus holding a vital role in the session's success.

Article 1 found the consultancy to conduct Co-Creations Sessions using techniques inspired by Design Thinking, Systems Engineering, Systems Architecting, and business theory. As part of the insight phase, the innovation consultancy performed user research by interviewing and interacting with users in their operational context. This user focus aligns well with the empathize phase in Design Thinking (Plattner, 2010) and stakeholder analysis in Systems Engineering (Walden et al., 2015). The insight phase also included research on enabling technology, market trends, and competitors, as we find in business model theory (Osterwalder & Pigneur, 2010). Stakeholder mapping and analysis is a common approach in Systems Engineering as part of the early systems development phase, while techniques to analyze the problem and solution domain are familiar in both Design Thinking (Plattner, 2010), (Brown & Wyatt, 2010), Systems Architecting (Muller, 2015), and business theory (Osterwalder, Pigneur, Bernarda, Smith, & Papadakos, 2014). However, playful (warm-up) exercises are more common in Design Thinking than in Systems Architecting and Systems Engineering.

The main results of Article 1 were the insight into the best engineering practices at the innovation consultancy and how Co-Creation Sessions supported exploration and early validation of innovative concepts. However, we also identified the need for an experienced facilitator to conduct successful sessions and reflected upon the skillset needed to facilitate such sessions.

4.2 Results and Discussions of Article 2

Title: Systems Thinking for Early Validation of User Needs in the Front End of Innovation; a Case Study in an Offshore SoS

Article 2 describes the results from conducting industry-as-laboratory (Muller, 2013; Potts, 1993) to research the best engineering practices at the EPCI supplier. The research context was the early systems development of a large-scale renewable energy system for operation in ocean space named Deep Purple. We actively engaged with the team developing the innovation for about three months, which later extended to a longitudinal study of about two years. The Deep Purple initiative led the EPCI supplier's transition towards renewable energy production systems. We observed the team lacking engineering practices to cope with the ambiguities and uncertainties during concept development and applied Systems Thinking methodology to support the team in clarifying system boundaries and communicating the business case to internal and external stakeholders. Article 2 focuses on the learnings from applying the Systems Thinking methodology.

In Article 2, we explored the use of Systems Thinking and Gharajedaghi's (2011) view on systems properties. We applied visual artifacts, such as a context diagram (Gharajedaghi, 2011, fig. 2.2) and Systemigram (Boardman & Sauser, 2008), to analyze systems openness, clarify systems boundaries, and communicate the system's value proposition and business case. Figure 10 shows the context diagram that identifies controllable and uncontrollable factors acting upon the Deep Purple concept, and Figure 11 shows the Systemigram of the Deep Purple concept in an offshore oil and gas production application.

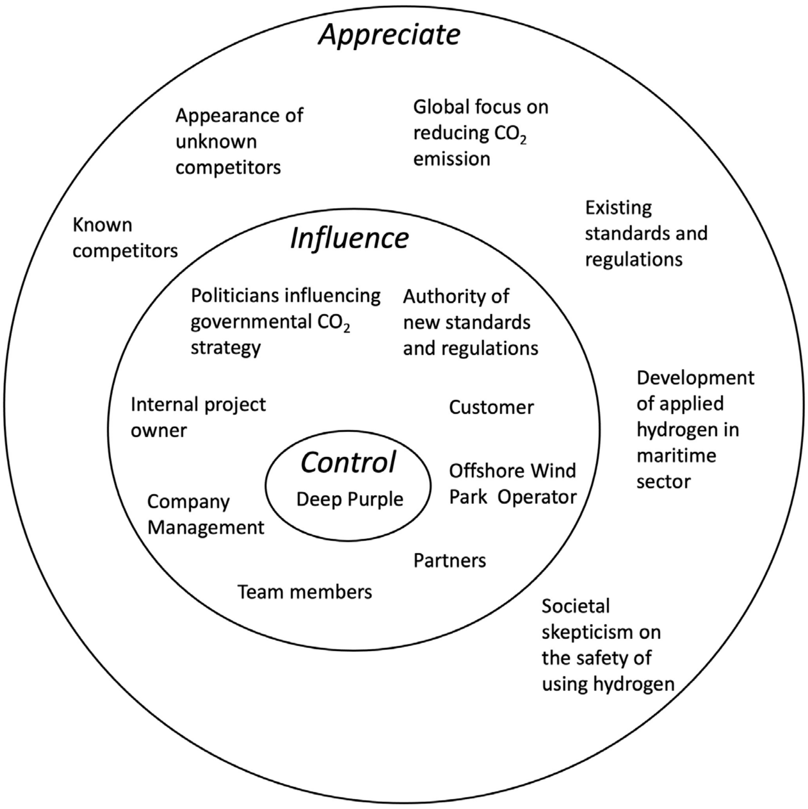

Figure 10. Context diagram of the Deep Purple concept (Article 2 © 2019 IEEE)

The context diagram analyzes the openness of the Deep Purple concept from the development team's perspective. Figure 10 shows the controllable variable in the center (development of the Deep Purple concept), the uncontrollable variables that the development team may influence in the middle layer, and the uncontrollable variables the development team cannot influence but will have to appreciate, in the outer layer.

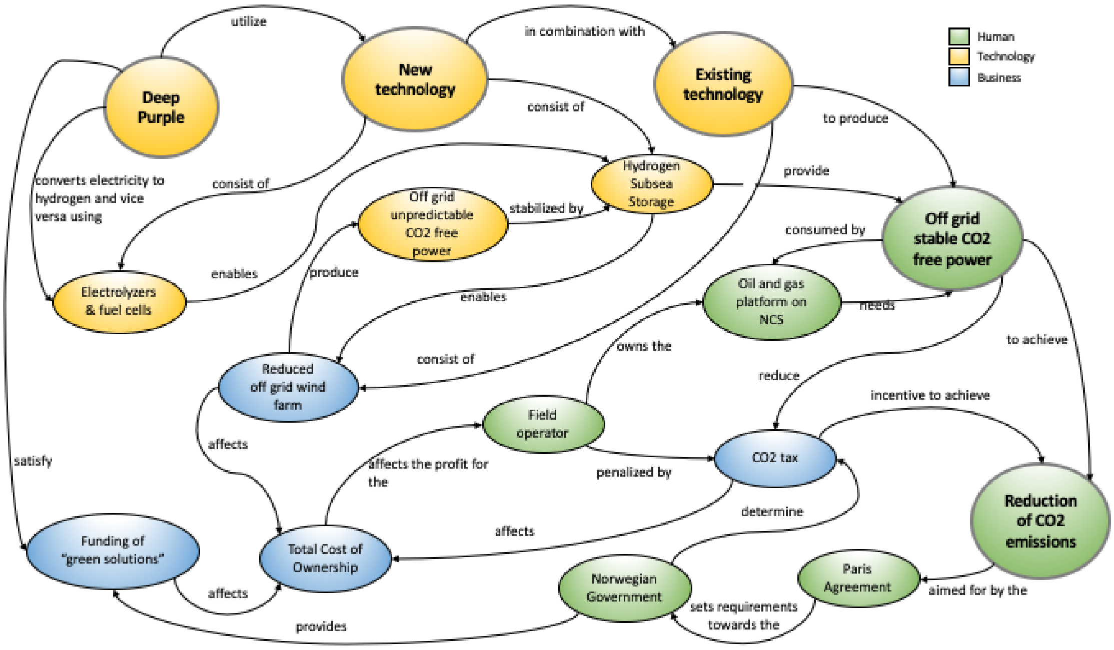

Figure 11. Systemigram visualizing the Deep Purple concept through technical, human, and business perspectives (Article 2 © 2019 IEEE)

The Systemigram shows how the concept provides value to internal and external stakeholders. The circles in bold font describe the mainstay of the systemigram: *"Deep Purple utilizes new technology in combination with existing technology to produce off-grid stable CO_2-free power to achieve a reduction of CO_2 emissions".*

Article 2 found it challenging and time-consuming to develop a Systemigram with a clear message and according to the design rules (Boardman & Sauser, 2008). The Systemigram shows the operational view of the system. However, we could not show other critical life cycle phases related to the user, such as installation and maintenance. Adding more Systemigrams showing the missing relations and views could most likely have solved this.

Furthermore, Article 2 found that analyzing the openness of Deep Purple using the context diagram was a low-effort and powerful technique to analyze stakeholders and gain clarities in system boundaries. On the other hand, developing a Systemigram was a slower but helpful technique to clarify the Deep Purple concept and its context. Rather than diving into the technical feasibility of the concept while communicating the system behavior to stakeholders, the Systemigram supported communication of other perspectives such as customer needs and value proposition.

The main results of Article 2 were insights into the lack of engineering practices at the EPCI supplier to support the exploration and validation of early phase innovative concepts. Furthermore, we gained insight into the importance of Systems Thinking to cope with the ambiguity and uncertainty of innovating in a socio-technical context. Compared to the insights gained from exploring the best engineering practices at the innovation consultancy, we found the EPCI supplier could benefit from adopting similar practices in their engineering processes to support exploration and early validation towards high-tech innovation.

4.3 Results and Discussions of Article 3

Title: Exploring a Co-Creative Problem-Solving Toolbox in the Context of Norwegian High-Tech Industry.

Article 3 builds on the insight gained in the Research Clarification and describes the industry partner's need derived in the clarification stage and the results from the Descriptive Study 1 that aimed to characterize a combined systems and design framework.

In Article 3, we analyzed ten industry cases exploring systems and design practices selected by the partners in the research collaboration project. This exploration of practices was a combined effort of the Ph.D. student and the researchers in the research collaboration project. The innovation consultancy proposed using Visual Canvas (Pinto et al., 2019), Interactive Knowledge Architecture (Jensen et al., 2019), and Co-Creation Session (Kjørstad, Falk, et al., 2019), while the academic partners proposed Gigamapping (Skjelten, 2014), Systemigram (Boardman & Sauser, 2008), and Illustrative ConOps (Muller et al., 2019; Solli & Muller, 2016).

Article 3 describes the industry needs that we derived from early interviews with the industry partners. Furthermore, Article 3 analyzes the industry cases to understand how the practices supported the needs and identify success criteria for a combined systems and design framework. The analyses include the experiences gained from researching Co-Creation Sessions in Articles 1 and Systemigram in Article 2. Table 7 shows the selected systems and design practices, while Section 3.1.2, Table 2 provides information about the industry case profiles and references to published results.

Table 7. Systems and design practices explored and analyzed in Article 3 (adapted from Article 3 © 2020 IEEE)

Practice	**Industry Case**	**Industry Partner**
Gigamapping	1	All four
Visual Canvas	2, 3	Innovation Consultancy
Interactive Knowledge Architecture	4, 5, 6	Ship designer, EPCI supplier, innovation consultancy
Systemigram	7	EPCI supplier
Illustrative ConOps	8	EPCI supplier
Co-Creation Sessions	9, 10	Innovation consultancy

Figure 12 shows small teams doing Gigamapping on the table and wall (in the back). Figure 13 shows each practice's main pros and cons, while Article 3 describes more details from each case.

Figure 12. Small groups doing structured Gigamapping (Article 3 © 2020 IEEE)

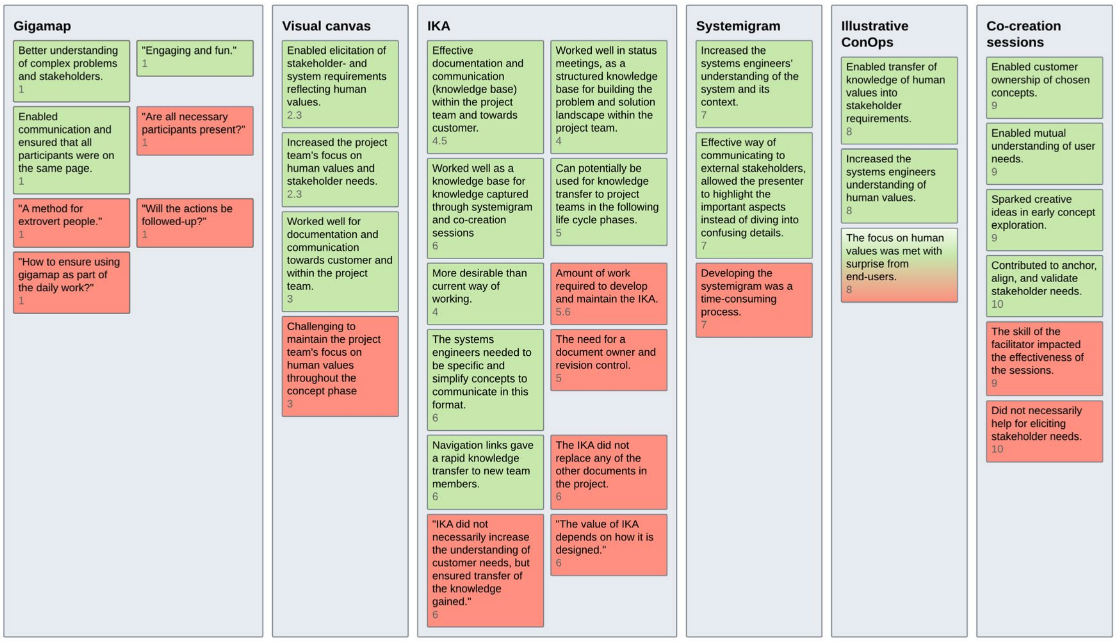

Figure 13. Pros and cons of the engineering practices analyzed in Article 3 (Article 3 © 2020 IEEE)[5]

Article 3 sharpened the research into three primary industry needs from the early interviews and focus groups with the industry partners. Figure 14 illustrates the industry needs in the context of a system's lifecycle.

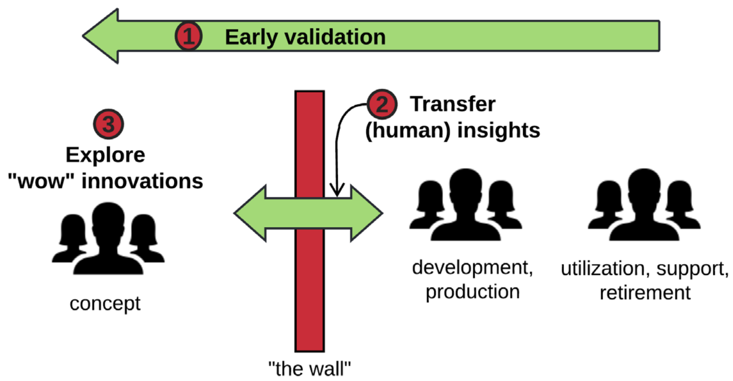

Figure 14. The industry needs in the context of a system's lifecycle (Article 3 © 2020 IEEE)

Firstly, the industry partners in the research collaboration project described challenges related to *early validation* (Figure 14, point 1) of innovative concepts. Late and costly

[5] IKA – Interactive Knowledge Architecture

design changes are often due to late validation, and the industry partners found it challenging to gain knowledge and insight at an early stage of how the system behaves in later life cycle phases, such as during installation and operation. Thus, they needed practices supporting early validation.

Secondly, the industry partners described challenges in *transferring the knowledge* (Figure 14, point 2) gained in early systems development to the teams working in later phases. The industry partners described the challenge related to this need as "*throwing concepts over the wall.*" currently not supported by heavy text-based design documents. Thus, they identified the need for practices to enable systems engineers to transfer this knowledge through the "*wall*."

Thirdly, the industry partners strived to *explore "wow"* innovations (Figure 14, point 3) to provide significant innovative services and systems to strengthen the business value and adapt to a rapidly changing market need. However, the industry partners found their current practices not sufficiently support exploring significant innovative concepts.

Building on the learnings from the Research Clarification stage, we identified success criteria for a combined systems and design framework that evolved as we continued to explore systems and design practices through industry cases. To verify the importance and relevance of the success criteria, we surveyed representatives from the four industry partners and analyzed the results using NPS. Table 8 shows the NPS results.

Table 8. Success criteria and their significance for the industry partners (Article 3 © 2020 IEEE)

SC	Success criteria	S1: Perceived importance for a new way of working	S2: Satisfied by the current way of working
1	Striving to fail early	-3	-8
2	Grasping complexity	2	-7
3	Showing business potential	4	-4
4	Sharing knowledge	1	-4
5	Visualizing	4	-4
6	Focus on customer	4	0
7	Enabling creativity	0	-3
8	Focus on user	1	-3

The industry partners identified *striving to fail early* and *grasping complexity* as the most challenging criteria to fulfill in the current way of working. Furthermore, the companies also perceived that they currently have enough *focus on the customer*. However, surprisingly, the industry partners were not promoting the two criteria; *striving to fail early* and *enabling creativity*.

These are factors often highlighted as essential for innovation, such as in the literature on Design Thinking (Brown & Katz, 2009; Kelley & Kelley, 2015; Lewrick et al., 2018). Reformulating the criterion "*striving to fail early*" into the more upbeat "*rapid learning*" might have provided a more favorable score from the industry partners. On the other hand, not promoting the criterion *enabling creativity* might be related to company culture and history. Based on the solid foundation in literature, we kept these two criteria.

To support exploration and validation of early phase concepts, Article 3 found that systems engineers may benefit from applying more collaborative and creative ways of working than supported by Systems Engineering. Collaboration expands the perspectives of the systems engineers and ensures stakeholder and context understanding, while creativity enables exploration of the problem space towards significant innovations. Co-Creation Sessions focuses on both collaboration and creativity by applying problem and solution exploration techniques. Such sessions require careful planning and strong facilitation skills. Rather than facilitate Co-Creation Sessions in its full, Article 3 proposed to find inspiration from the techniques applied in the sessions and make use of shorter and more iterative sessions.

To further support systems engineers to explore and early validate concepts towards a system's operational life cycle, Article 3 found that systems engineers need practices to explore user needs and operational scenarios. Tools such as Visual Canvas and Illustrative ConOps are suitable for this purpose. Making visualizations forces the system engineers to simplify ambiguous concepts. The outcome of the Illustrative ConOps and Systemigrams is a tangible artifact that eases discussion in the team and with customers. Storing this artifact in a knowledge base, such as Interactive Knowledge Architecture, supports the transfer of insights towards later life cycle phases. Based on the findings from the cases applying Interactive Knowledge Architecture, Article 3 proposed to integrate such a knowledge base to a more formal architectural framework, similar to what was proposed by Cloutier, Sauser, Bone, and Taylor (Cloutier et al., 2015). A digitized Interactive Knowledge Architecture may reduce manual updates and ease configuration management. However, the knowledge base should still strive to keep an intuitive and desirable format for the systems engineers to use.

Article 3 found practices supporting knowledge sharing to be multidimensional. Session-based practices, such as Gigamapping and Co-Creation Sessions, support sense sharing between people as part of a sense-making process. Sense-sharing is essential for a team to make sense of complex problems. However, the insights gained during such sessions also need to transfer to people not being part of the process. Thus, we need to capture and transfer the insights gained from sense sharing into the knowledge base. The capture and transfer of insights require systems engineers who have the skill to order and visualize such knowledge. Making Systemigram supports sense sharing by the people part of the process, and the Systemigram itself enables knowledge sharing to people not part of the process. Our findings from the case show that systems engineers may perceive the process of making Systemigram as time-consuming. The value of Systemigram needs to be clear for the systems engineers to apply it in their daily work.

The main results of Article 3 were insights into the main industry needs for engineering practices supporting exploration, early validation, and knowledge transfer in systems development. We identified eight success criteria for a combined systems and design framework: understanding stakeholder needs (customer, user, and business) and exploring and validating early systems design using visualizations, creative techniques, and knowledge sharing. Article 3 found the practices to complement each other in supporting the industry needs and identified the need for a flexible framework to support systems engineers with different skills and ways of working. Finally, Article 3 proposed further research on engineering practices using collaboration and creativity and laid the foundation for Article 4.

4.4 Results and Discussions of Article 4

Title: Co-Creative Problem-Solving to Support Rapid Learning of Systems Knowledge Towards High-Tech Innovations: A Longitudinal Case Study.

Article 4 builds on the research in Article 3 and describes results from the Prescriptive Study and Descriptive Study 2. The first part of Article 4 aimed to synthesize a practical method employing the success criteria identified in Article 3. The second part of Article 4 aimed to identify the main challenges in applying the method in an industrial application.

4.4.1 Part 1

In Article 4, we conducted action research to continue researching the systems development of the large-scale renewable energy systems in the development team at the EPCI supplier. All in all, we actively engaged with the development team in a longitudinal study of about two years. In the Prescriptive Study, we planned and conducted nine exploration and validation sessions guided by the success criteria identified in Article 3 (Section 4.3, Table 8). In addition, we used practices that fit the team's specific needs and context of each session, building on the learnings from Article 3 and the literature review in Section 2.6.

We analyzed the sessions and identified capabilities for a combined systems and design framework and impacting factors on practical implementation. After that, we integrated the capabilities and impacting factors into a practical method. Finally, in Descriptive Study 2, we passively observed the development team applying the method in two sessions. Section 3.1.3, Table 3 informs of the sessions' profiles, while Table 9 provides an overview of the practices and artifacts explored in the sessions.

In the first session, we observed the participants conducting a workshop using a hazard identification analysis of the renewable energy concept to gain insight into the EPCI supplier's best engineering practices in conducting sessions.

Table 9. Practices and artifacts explored and analyzed in the in-depth industry case at the EPCI supplier (adapted from Article 4)

Session	Practices and techniques	Artifacts
S1	Hazard identification analysis (HAZID)	System drawing on A3 printout, guide words on A4 printout, projector, scribe
S2	Technology Readiness Levels (TRL), guide questions, technology qualification procedure	Guide questions on A4 printout, review procedure on A4 printout, sticky notes, flip overs, large paper plot, markers
S3	Timeboxing, free-format Gigamapping with Z-analysis	Large paper plot on table, flip-overs, markers, need statement on A4 on the wall
S4	Free-format Gigamapping including ZIP-analysis	Large paper plot on table, flip-overs, markers
S5	Timeboxing, warm-up exercise, CAFCR light, individual and group ideation, add concept constraints	Superhero exercise A4 printout, flip-overs, whiteboard, markers, sticky notes, large paper plot on table, system drawing on A3 printouts on the wall
S6	Brainwriting 6-3-5, adjusted to 5-2-4	Projector showing visualization of a pilot project, brainwriting form on A4 printouts
S7	Timeboxing, individual and group ideation	Flip-overs, markers, sticky notes
S8	Timeboxing, Pugh matrix, individual ideation	Projector showing Pugh matrix, sticky notes
S9[6]	Timeboxing, CAFCR light, individual and group ideation, Pugh matrix	Introducing concepts on a projector, system drawings on printouts on the wall, sticky notes, large paper plot, markers

In Sessions 2 to 8, we applied Brainstorming (Osborn, 1953), Brainwriting (Silverstein et al., 2012, Chapter 20), and Gigamapping (Skjelten, 2014) for ideation. In addition, we used other techniques to stimulate creativity, such as co-evolving on problem and solutions spaces (Dorst, 2019; Dorst & Cross, 2001), combining individual and group exercises (Paulus & Nijstad, 2003), and challenging operational scenarios of concepts through adding or removing constraints (The Ideas Centre, 2020).

We also explored CAFCR (Muller, 2004), focusing on connecting desired systems qualities to the systems realization and identifying gaps and trade-offs. We explored the use of a playful warm-up exercise inspired by Design Thinking in Session 5. Furthermore,

[6] In S9, we could not conduct the session according to plan and did not explore any co-creative techniques. We include the findings from this session as they provide valuable insight into impacting factors for the method’s applicability

we used large paper plots, visualizations, markers, sticky notes, flip overs, and a whiteboard. Figure 15 and Figure 16 show two of the sessions conducting ideation and concept review, respectively.

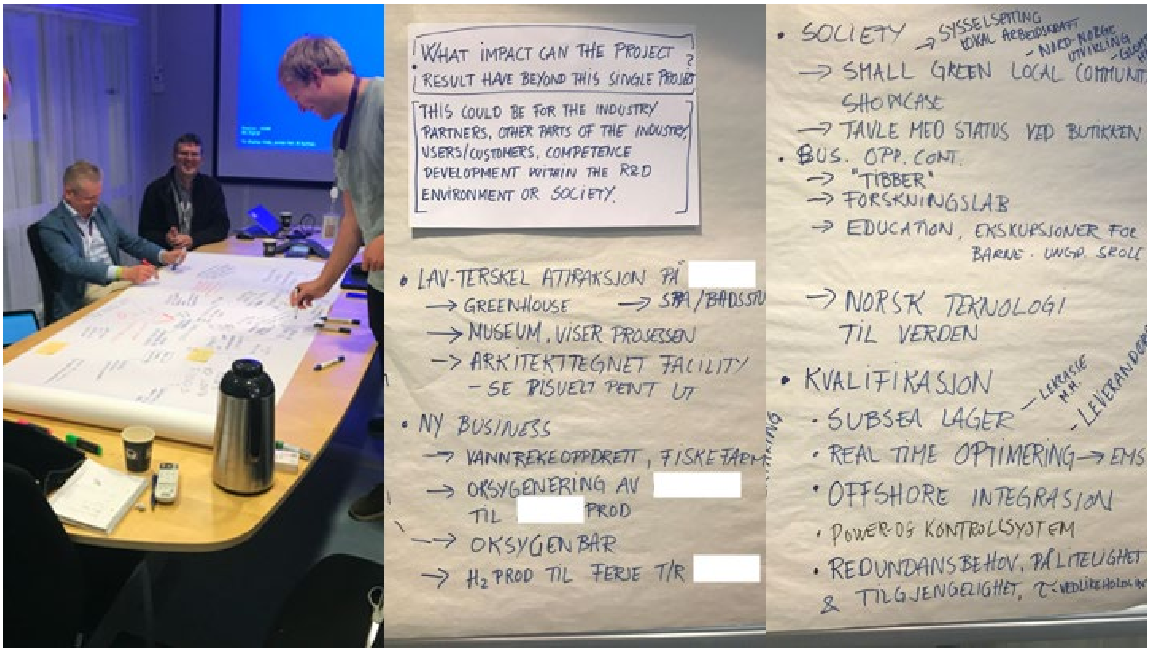

Figure 15. Pictures from a session exploring ideas for a pilot study

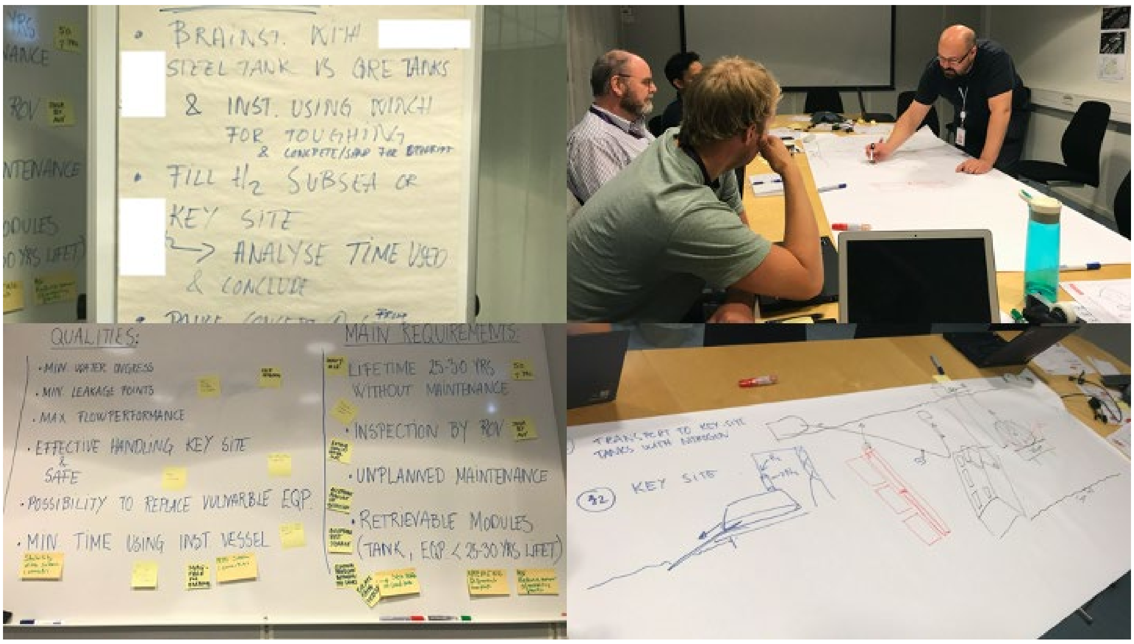

Figure 16. Pictures from a session validating an early concept

Article 4 describes the learnings from the sessions and identifies three main capabilities of applying such sessions. The capabilities are a thorough *problem and solution exploration* to avoid engineers jumping to solutions, a *collective creation* of the system concept to ensure shared maturity of systems knowledge and ownership, and the ability to *think creatively* to explore and challenge the system boundaries. As we explored sessions, we also identified impacting factors of the practical application of sessions. In the method synthesis, we implemented the capabilities and impacting factors into a method that supported the facilitator's and problem owners' upfront understanding of the problem and need using brief sessions and a timeline. Figure 17 illustrates the method that includes a three-stage process to plan and conduct the sessions using the timeline.

The method distinguishes from an expert-led co-creation workshop, such as the Co-Creation Sessions applied at the innovation consultancy in primarily two ways:

- it supports the use of inexperienced facilitators to conduct the sessions, as the systems engineers in the industry case lacked such experience;
- it emphasizes the use of brief sessions to fit within a busy workday for the participants in the industry case.

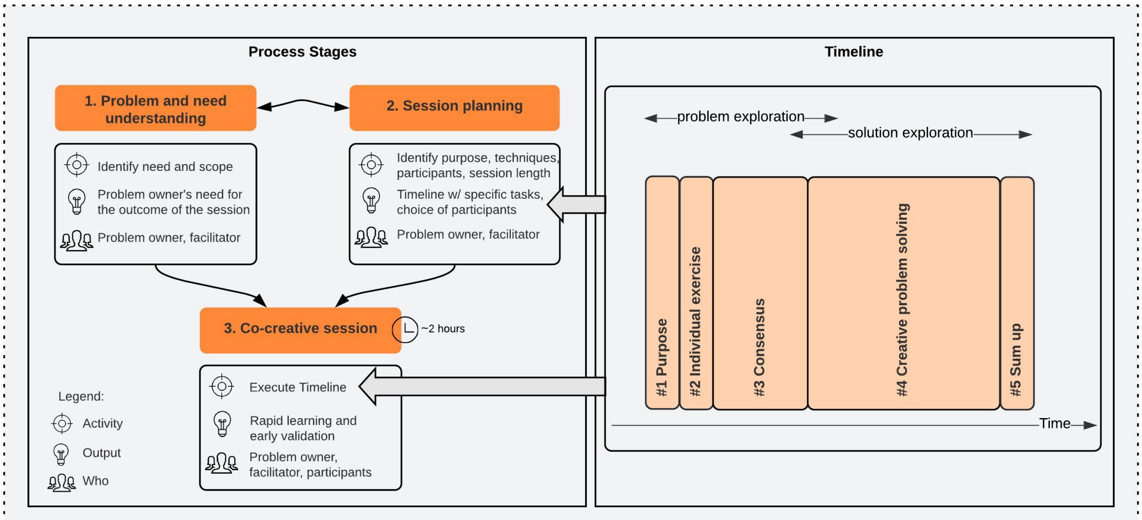

Figure 17. The framework's capabilities implemented into a practical method (Article 4)

Firstly, the method splits the roles of the problem owner and the facilitator. Paulus et al. (2003) and Muller (2018b) described a similar approach for creative groups and workshops. The problem owner holds the system's insight and need for progress on the problem and thus has the incentive to take on this role. The facilitator leans on the problem owner for support during the session to share knowledge of the problem. Secondly, the method makes use of brief sessions using inexperienced facilitators. The systems engineers in the industry case lacked facilitation experience, and shorter sessions are often easier to facilitate than full-day workshops.

Figure 18 illustrates how the sessions may provide the capabilities using the success criteria as a guide during planning. The solid lines illustrate a strong connection between the success criteria and the capabilities, while the dotted lines illustrate a weaker connection. The following paragraphs elaborate on how the capabilities connect to the success criteria.

Firstly, Article 4 defines *problem and solution exploration* as exploring both the problem and the solution space in the session, considering enabling technology, business case, customer needs, and user needs. Typically supported by the success criteria *showing business potential*, *focus on the customer*, and *focus on the user*.

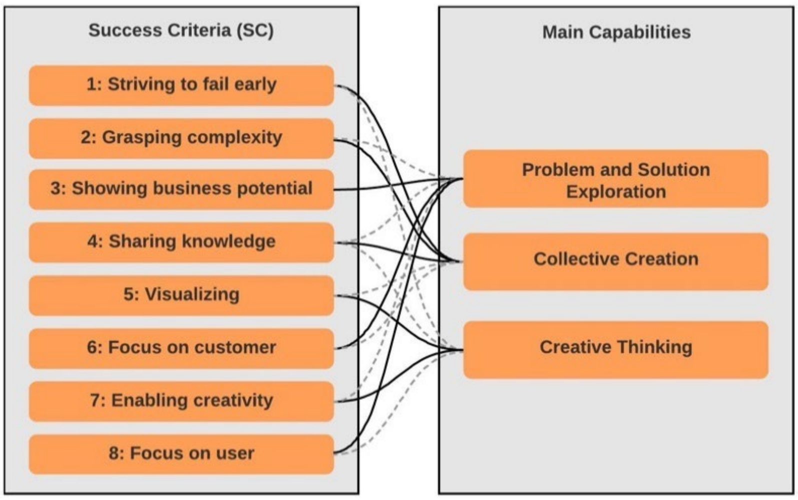

Figure 18. Mapping success criteria to the identified capabilities of the proposed method (Article 4)

The literature supports the importance of a good problem and solution exploration towards innovation (Bono, 2016; Daly et al., 2012; Dorst, 2019; Dorst & Cross, 2001; McFadzean, 1998, 2000; Murray et al., 2019). Bonnema, Veenvliet, and Broenink (2016, p. 9) identified solution focus as a challenge among engineers in development teams and claimed that "*many engineers think in solutions*". The timeline aims to support a structured problem and solution exploration and thus prevent such fixation. Furthermore, we found it essential that the participants held the required knowledge to conduct problem and solution exploration. Such knowledge typically includes insight into customer needs by *focusing on the customer,* systems operational context by *focusing on the user*, and enabling technology and business case by *showing business potential*.

Secondly, Article 4 defines *collective creation* as exploring or maturing an idea or concept in the session with a high degree of uncertainty and complexity. Typically, this requires striving for early failures, grasping complexity, and knowledge sharing. Co-Creation and Co-Design focus on collective creativity in value creation (Prahalad & Ramaswamy, 2004) and design development (E. B.-N. Sanders & Stappers, 2008). Systems approaches such as Systems Engineering and Systems Architecting emphasize collaboration and creativity in concept generation (Pugh, 1981, 1990) and systems development (Maier & Rechtin, 2009; Muller, 2004; Sage & Armstrong, 2000; H. G. Sillitto, 2009). To support collective creation, we aimed for *knowledge sharing* of early phase concepts and strived for *early failure* by sharing multiple perspectives using techniques such as CAFCR (Muller, 2004). We also applied techniques to support the participants in *grasping complexity*, such as Gigamapping (Sevaldson, 2018).

Thirdly, Article 4 defines *creative thinking* as exploring multiple perspectives and challenging perceived boundaries during problem and solution exploration and supported by visualization and enabling creativity. We applied a variety of means to *enable creativity* and support creative thinking. Human-centric approaches, such as Design Thinking, emphasize creativity to explore innovative concepts (Brown & Katz, 2009). Firstly, the sessions applied engaging and creative techniques, such as brainwriting (Silverstein et al., 2012, Chapter 20). Secondly, the sessions applied time constraints using timeboxes (Muller, 2009) to push the participants to engage and create. Thirdly, the timeline combines individual and group exercises to ensure all participants share their perspectives and build on each other's ideas and thoughts. Paulus et al. (2003, Chapters 6, 7) emphasized the importance of combining individual and group exercises to enhance creativity. Finally, the sessions applied *visualizations* to enable creativity, also highlighted in similar creative workshops (Kerzner, Goodwin, Dykes, Jones, & Meyer, 2018) to stimulate creativity, create sketches collectively in the session, or prepare visualizations before the session.

The main results of Article 4, part 1 were insights into how a method focusing on problem and solution exploration, collective creation, and creative thinking may support systems engineers to innovate in a context of socio-technical complexity. Furthermore, Article 4, part 1 synthesized such a method to support systems engineers in the industry case to explore and early validate innovative concepts during systems development.

4.4.2 Part 2

In Descriptive Study 2, we passively observed the systems engineers in the development team apply the method in two sessions. After the sessions, we conducted informal interviews with the facilitator and the problem owner. This initial evaluation aimed to identify the main challenges in achieving the capabilities in an industrial setting. Section 3.1.4, Table 4 informs of the sessions' profiles.

In Session A, we found the method supported the systems engineers in planning and conducting a structured problem and solution exploration with stakeholders. We observed the facilitator and the problem owner struggling to gain insight into the problem upfront in Session B. The facilitator planned to conduct creative problem-solving techniques on the fly, resulting in a session where the facilitator struggled to facilitate and failed to apply a creative technique. The session resulted in mainly talking. In both sessions, we observed that the facilitator and the problem owner succeeded in including participants holding the needed knowledge for early validation of essential aspects such as business case, value proposition, and enabling technology.

When comparing to research on similar methods, we find that McFadzean identified the usability of practices focusing on collective creativity in engineering teams dependent on the participants' willingness and ability to engage in such activities (McFadzean, 2002a, 2002b). This way of working is unfamiliar to some people and challenges their comfort zones and their perception of acceptable ways of working. Setting session rules or informing participants upfront of what creative problem-solving techniques are may support people to feel less uneasy and prepare for engaging in this new way of working. While exploring the sessions, we observed that once the participants familiarized themselves with creative problem-solving techniques, most seemed to approve and appreciate this way of working.

The main results of Article 4, part 2, were an initial evaluation of the proposed method in the industry case. The evaluation identified main potential challenges for a successful application, such as lack of facilitation skills and inexperience with applying creative techniques among systems engineers in the industry case.

4.4.3 Additional Results (not included in Article 4)

As part of the Descriptive Study 2, we approached the industry partners for feedback on how the method could provide value in their context to gain insights into the method's context dependencies. We received feedback from two industry representatives from the innovation consultancy, one from the ship designer and one from the EPCI supplier from a different part of the organization than the development team.

The industry representatives highlighted the following potential benefits of the method:

- a structured way of working
- provides a collective understanding of objectives
- shares knowledge and perspectives

- supports problem owners toward their goals, and the organization towards their sub-goals
- use of visual tools to engage all participants
- practical usable (low-cost, easy to use)

Furthermore, they identified the following potential challenges for making use of the method:

- a current gap in facilitation skills
- to implement a new way of working
- a current gap in experience using creative problem-solving techniques
- to know when to use the method
- to define the problem owner

Finally, they identified the following potential use of the method in their companies:

- co-creating with customers in concept development to support problem understanding
- to find viable solutions on how to improve internal work processes that do not work
- a guide to improving the outcome of internal workshops run in the company
- clarifications of systems qualities in collaboration with the customer in front end studies

We found that the industry representatives perceived the method valuable but expected to face similar challenges to apply the methods as identified in Article 4, such as a lack of facilitation skills and lack of experience in using creative problem-solving techniques. Furthermore, the partners foresaw challenges in employing the method as they were unsure when to use it. Position the method in the company's engineering processes may clarify when to apply the method and identify relevant roles and responsibilities.

The main results of the additional evaluation were insights into how to apply a similar method at the other industry partners, the perceived challenges in an application, and the importance of supporting engineering processes to guide the systems engineers in how and when to best use such methods.

5 Validation

This chapter discusses the validity of the research results presented in Chapter 4, using the approach to validation described in Section 3.5. This chapter aims to provide transparency and insight into how validity threats may impact the credibility of the results in this thesis.

Maxwell (2013) proposed an eight-point checklist for testing the validity of the conclusion and the existence of potential threats to the conclusion; long-term involvement, rich data, respondent validation, intervention, negative cases, triangulation, numbers, and comparison. Further, Maxwell described two specific validity threats in qualitative research; bias and reactivity. The following subsection discusses the credibility of the findings in this thesis concerning Maxwell's checklist. After that, we discuss the role of bias and reactivity in this thesis.

5.1 Credibility of Findings

1. **Intensive, long-term involvement.** In the industry cases conducted in this research, we engaged with the systems engineers for about three months to two years. The long-term involvement enabled us to familiarize ourselves with the project teams, taking on their language, rules, and behavior. We argue that this made the team members feel at ease with an external researcher and reduce the researcher's influence on the research setting. Further, this approach allowed us the gain insight into what worked well within the team and what did not work well, thereby reducing the researcher bias.

2. **Rich data.** Throughout the research, we focused on collecting rich qualitative data in multiple contexts and from different perspectives, seeking to gain an in-depth understanding. We used the research logbook to store the data (Section 3.2, Table 5), and we produced a variety of artifacts to analyze the results (Section 3.2, Table 6). We argue that such varied and detailed data collection reduced researcher bias and reactivity.

3. **Respondent validation.** Further, we shared and discussed findings with research objects as a natural part of the intervention in the industry cases. We strived for transparency about our findings to our research partners throughout the research. We also shared and discussed research findings in six half-yearly workshops with the industry partners. Both industry and academic partners provided valuable feedback and perspectives throughout the thesis.

   We obtained feedback from the industry partners primarily through informal discussions, surveys, debriefs, and workshops. In addition, we obtained feedback from the academic supervisors through regular meetings and academic partners through less regular discussions and workshops. The feedback contributed to the research design and reflections of the research results.

4. **Intervention.** Intervention is a natural part of the action research strategy and hence of this research. We actively engaged with the systems engineers at the industry partners in various degrees throughout the research. To a medium degree in Descriptive Studies 1 and 2 and a higher degree in Prescriptive Study while intervening with the development team at the EPCI supplier.

   Intervention with the industry partners through industry cases in Descriptive Study 1 enabled an in-depth understanding of the challenges in current engineering practices, industry needs, and how to describe a practical framework. Further, intervening with the development team at the EPCI supplier in the Prescriptive Study enabled us to identify the framework's capabilities and synthesize a practical method to support the capabilities. Furthermore, intervening with the development team in Descriptive Study 2 provided insight into the main challenges in applying such a method in an industrial setting.

5. **Searching for discrepant evidence and negative cases.** We searched for discrepant evidence and negative cases while exploring systems and design practices in

Descriptive Study 1 and synthesizing a practical method in Prescriptive Study. Article 3 searched for negative cases by identifying the pros and cons of practices explored in the industry cases. Article 4 describes how negative cases were part of the method synthesis, building on the elements that worked well and removing or strengthening elements that did not work out.

6. **Triangulation.** In this research, we actively participated in numerous project meetings, workshops, and sessions to collect relevant data from multiple contexts. We collected data using different data collection methods chosen for the purpose and research need. However, we see the need for further research to evaluate and adapt the proposed method for other settings than the development team at the EPCI supplier, such as other project teams and organizations with similar challenges.

7. **Numbers.** This research has been primarily qualitative, using numbers to a low degree. We used numbers in the form of an NPS analysis to evaluate success criteria for the framework in Article 3 and to analyze sessions in Article 4. We also applied numbers to score how the sessions supported the capabilities in Article 4. Numbers based on qualitative findings may provide more explicit arguments than we provide in this thesis (Maxwell, 2013). We see the need for further research to provide more confident numbers that can strengthen the credibility of the research.

8. **Comparison.** Article 3 identifies the primary industry needs of the four industry partners to be similar. However, their domains, organization, and engineering processes are slightly different and provide different contexts for the research. To strengthen the initial evaluation of the proposed method, we approached the industry partners for feedback to compare research settings in Descriptive Study 2.

5.2 Researcher Bias and Reactivity

Researcher bias describes how the researchers' values and expectations may affect their approach and conclusion. The reactivity describes how the researchers influence the research setting (Maxwell, 2013). Maxwell's goal was not to eliminate the threats as they are reflecting the nature of qualitative research. However, he highlighted the importance of understanding how such threats may impact the correctness of the conclusion.

We actively engaged with the engineers to understand the industry challenges and potential solutions, taking on their language, rules, and behavior over a longer time horizon. Blessing et al. (2009, p. 259) highlighted the advantage of using such participatory observations for in-depth understanding. However, they pointed out the need to carefully consider the dilemma between subjectivity and objectivity in the research results obtained through such observations. Further, Blessing et al. proposed strengthening the awareness of this challenge through distinct notetaking reflecting upon the following types of notes; *observational, interview, methodological, reflective, theoretical,* and *organizational*. Throughout the research, we conducted careful notetaking reflecting upon various dimensions as proposed by Blessing et al. Section 3.2. Table 5 and Table 6 show the main types of data collected and the artifacts produced for analyzing and synthesizing the data. *Observational*, *interview*, *reflective*, and *organizational* notes were primarily part of the digital research logbook in Evernote. In addition, we used the notes functionality in the reference management system to note findings in the literature (*theoretical*). Likewise, we used MS PowerPoint to note comments on the research design (*methodological*) and the other artifacts made during the research, such as the presentation of the method synthesis.

We adapted the research design to the specific need and purpose in each research stage. Further, we strived to discuss research results with research subjects, partners, and supervisors to gain multiple perspectives. We produced various artifacts for discussions (Section 3.2, Table 6). Such as MS PowerPoint presentations of industry cases, including write-up of the case, survey results, and results from debriefing participants. Further, we discussed the results while actively engaging with the engineers at their workplace. We also discussed research results with research partners at the six half-yearly workshops conducted through the research project. This approach strengthened the researcher's confidence in the interpretation of results and chosen research design.

Maxwell pointed out that participant observation usually influences the participant's behavior less than other research methods such as formal interviews. To cope with reactivity, we carefully chose research methods regarding purpose and research context. We argue that the long-term involvement in the project team at the EPCI supplier while synthesizing the proposed method reduced the threat of reactivity.

The research in the development team at the EPCI supplier ended up with a two-year longitudinal study, and we gained a thorough insight into their challenges in the early phase of systems development and their ways of working. The main reasons for staying with the development team for two years were practical and research-related. Getting access to an industrial research environment is challenging when not employed in the industry. As the team welcomed the Ph.D. student into the team, this was a promising way forward to conduct an in-depth industry case, gain insight into their daily challenges, and synthesize a practical method.

This research might have progressed in a different direction if we had chosen to gain an in-depth understanding of an industry case at the innovation consultancy when sharpening the research. The focus of the research would perhaps be even more on empathizing with users, and the theoretical positioning would most likely be closer to design than systems theory. In addition, the research context would most probably be within the context of product innovations rather than a large-scale complex system of systems. The choices made might have been steered by the Ph.D. student seeking an industry context similar to her previous experience and interests and by the availability of a fit industry context at the time of research sharpening.

6 Conclusion

This chapter concludes the thesis' main findings by revisiting the research goals and questions introduced in Section 1.4. Then, it reflects on the thesis contributions and provides an outlook for further research.

This research has primarily conducted action research in the context of four Norwegian high-tech industry partners as part of a research collaboration project funded by the Norwegian Government. The main vision of the industry partners was to establish a Human Systems Engineering Innovation Framework (H-SEIF) by bridging Systems Engineering and Design Thinking. This research transformed the vision into a combined systems and design framework to support exploration and early validation in systems development towards significant innovations.

In recent years, the literature has proposed combining systems and design approaches to cope with the complexity of real-world problems in systems development. However, the literature on practices to support this combination is still young. Even though the Systems Engineering body of knowledge proposes combined frameworks, there is a knowledge gap of practical ways of working to achieve this. In this research, we focused on approaches such as Systems Thinking, Systems Architecting, Systems Oriented Design, Participatory Design, and Design Thinking to support Systems Engineering practices towards high-tech innovations.

6.1 Revisiting the Research Questions

RQ1: *What are the desired characteristics of a combined systems and design framework supporting systems engineers in the early systems development phase?*

RQ1-a) What are the industry partners' needs for a combined framework?

To address sub-question *1a)*, the research conducted informal interviews and focus groups with the industry partners over several months (Kjørstad et al., 2020).

The research identified the industry partners in need of engineering practices to support *early validation* of the operational usage of the system, *transfer of knowledge* to development teams in subsequent life cycle phases, and *exploration* of innovative concepts leading to significant innovations rather than incremental.

RQ1-b) How do the explored engineering practices support the industry partners' needs?

The research explored systems and design practices in ten industry cases at the industry partners. To address sub-questions *1b)*, Kjørstad et al. (2020) analyzed the pros and cons of applying the practices at the industry partners. The industrial applications were in early systems development ranging from small-scale product innovations to large-scale system of systems innovations. The research explored Visual Canvas (Pinto et al., 2019), Interactive Knowledge Architecture (Jensen et al., 2019), Co-Creation Session (Kjørstad, Falk, et al., 2019), Gigamapping (Skjelten, 2014; Wettre et al., 2019), Systemigram (Boardman & Sauser, 2008) and Illustrative ConOps (Muller et al., 2019; Solli & Muller, 2016). The practices positions in Systems Architecting (informal practices), Systems Thinking, Systems Oriented Design, Participatory Design, and Design Thinking.

The research found the practices to support the systems engineers in rapidly gaining insight into operational needs, customer value proposition, and business cases by applying visualization, creative techniques, and sense-sharing during problem-solving. Kjørstad et al. (2020) derived desired success criteria for a framework being striving to fail early (SC1), grasping complexity (SC2), showing business potential (SC3), sharing knowledge (SC4), visualizing (SC5), focus on the customer (SC6), enabling creativity (SC7), and focus on the user (SC8).

RQ1-c) What may be the outline of a framework?

To answer sub-question *1c)*, Kjørstad et al. (2020) built on the learnings from exploring the practices at the industry partners and identified the need for a flexible framework supporting systems engineers with different skills and ways of working.

The research found that a combined systems and design framework should support systems engineers to balance exploration and early validation in systems development. Furthermore, the research found that the practices should support systems engineers to create tangible artifacts to decrease uncertainty and enable rapid learning of systems knowledge. Kjørstad et al. (2020) proposed further research on employing the success criteria in a session-based method to support the systems engineers at the EPCI supplier in systems development towards high-tech innovations.

RQ2: *How can systems engineers employ such a framework in a context of socio-technical complexity?*

RQ2-a) How can the framework support systems engineers at the EPCI supplier in rapid learning and early validation?

To address sub-question *2a)*, the research explored a session-based method employing the success criteria identified in RQ1-b) in a longitudinal industry case at the EPCI supplier. The systems engineers in the industry case were in the early systems development phase of a large-scale renewable energy system holding a high degree of complexity and ambiguity. The sessions aimed to support systems engineers in exploring and early validating systems concepts in collaboration with project stakeholders such as project managers, business developers, and subject matter experts.

From analyzing the sessions, Kjørstad et al. (2021) identified the sessions to provide three main capabilities; *problem and solution exploration* to prevent solution focus and jumping to solutions (1), *collective creation* to explore and mature system concepts with a high degree of uncertainty and complexity (2), *creative thinking* to explore multiple perspectives and challenging perceived system boundaries (3).

RQ2-b) How may the systems engineers at the EPCI supplier employ the framework using a practical method?

In light of sub-question *2b)*, this research synthesized the learnings from exploring the session-based method in the industry case into a practical method (Kjørstad et al., 2021).

The research identified the main impacting factors as the *role separation of the problem owner and the facilitator*, the *upfront problem understanding*, and the *session length*. To support the capabilities identified in RQ2-b), this research synthesized a session-based method consisting of a three-stage process and a timeline. The timeline aimed to support systems engineers in a structured problem and solution exploration applying creative techniques using brief sessions and facilitators holding a low degree of facilitation experience, such as the systems engineers in the industry case at the EPCI supplier.

RQ3: *What may be the main challenges for systems engineers to employ such a framework?*

RQ3-a) What may be the main challenges for the systems engineers at the EPCI supplier to apply the method?

In light of sub-question *3a)*, this research gained insight into the session-based method's main challenges by applying the method in the development team at the EPCI supplier. Kjørstad et al. (2021) passively observed systems engineers applying the method in two sessions. The research found the method supporting the systems engineers to reflect and share insights on the problem before conducting sessions. The up-front understanding of the problem space is essential to conduct successful sessions. Furthermore, we identified the main challenges in achieving the capabilities as the lack of skills in facilitating and lack of experience in using creative techniques.

RQ3-b) How can the method support systems engineers at the other industry partners?

To address sub-question *3b)* the research approached the industry representatives to gain insights into the method’s context dependencies. The representatives described the method's potential benefits as sharing knowledge and perspectives and providing structure to support problem owners in reaching their goals. However, the partners foresaw challenges in employing the method as they were unsure when to apply it. This uncertainty may imply a lack of supporting engineering processes. Furthermore, they identified potential challenges in applying such a method as a lack of facilitation skills and lack of experience in using creative problem-solving techniques among the systems engineers.

6.2 Contributions

This thesis contributes to the Systems Engineering body of knowledge by gaining insight into the industry needs for a combined systems and design framework in the early systems development phase. The thesis identifies the characteristics of a combined systems and design framework and broadens the theoretical understanding of how such a framework supports the engineering practices towards high-tech innovation. Furthermore, the thesis proposes a practical method to guide the systems engineers in employing the framework and indicates potential challenges and lack of skills among systems engineers to practice the framework. Table 10 lists the theoretical and practical contribution this thesis may provide in light of the results presented in the appended articles.

Table 10. Summary of the appended articles' theoretical and practical contributions

Article	Theoretical Contribution	Practical Contribution
1	Capturing tacit knowledge on engineering practices utilizing Co-Creation sessions to explore and early validate innovative concepts in systems development	Systems engineers may use the results from the industry case as input to establish practices using Co-Creation Sessions for problem and solution exploration in collaboration with customers and users
2	Add to the knowledge base on practical implication of applying Systems Thinking methodology in mature companies to cope with complex problems in systems development towards significant innovations	The results may provide practical implications for systems engineers in how to clarify system boundaries and communicate business cases using context diagrams and Systemigram
3	Add to the knowledge base on how a combined systems and design framework in Systems Engineering may look like and what type of practices to employ in such a framework	The results may provide practical implications for systems engineers in need of practices to explore and early validate innovative concepts facing similar industry challenges
4	Add to the knowledge base on how systems and design practices focusing on collaboration and creativity support exploration and early validation in systems development of significant innovations	Systems engineers may use the proposed method in similar contexts to explore and early validate innovative concepts in systems development towards high-tech innovations

	Add to the knowledge base on the main challenges in practicing a combined systems and design framework in an organizational context not accustomed to this way of working Furthermore, the results may contribute to research on Systems Engineering's competency framework by identifying potential lack of skills among systems engineers to practice a combined systems and design framework	

6.3 Limitations and Recommendations for Future Work

This research primarily builds on action research (Checkland & Holwell, 1998) using qualitative data collection methods. Action research and similar participatory approaches are applied in research on Systems Engineering to gain an in-depth understanding of industry challenges and improve (Falk & Muller, 2019; Muller, 2013; Valerdi, Brown, & Muller, 2010). However, these research approaches increase the risk of researcher bias and challenge the generalization of research results. This thesis strived for validity in research results by focusing on long-term involvement, triangulation of data collection methods, and rich data collection from multiple perspectives.

This research has been conducted in the context of four Norwegian high-tech industry partners and recognizes the effect of the Norwegian organizational culture on the research results. Furthermore, the research recognizes that a sample of four industry partners does not fully represent the Norwegian high-tech industry. Therefore, we cannot claim the validity of research results for other industry contexts than described for each research stage and propose further research to collect data from various contexts generalizing research results. The research context varied between the Norwegian high-tech industry partners as the research progressed and may have further impacted the research results. The industry partners chose the explored practices as the research progressed, and we consider that the chosen practices may have impacted the research results. Further research is needed to evaluate and consider alternative practices supporting the same ends.

The H-SEIF research collaboration project provided learnings to the industry and the body of knowledge in 13 publications, a popular science booklet, nine master theses, and this Ph.D. thesis. The remaining open questions are how to position the learnings into a new framework and make value for the industry systemically applying the framework. The subsequent stage of the research collaboration project started in fall 2020, aiming to build on the learnings and connect to the digitalization and big data era that currently has a high focus in the industry (USN, 2020).

We recommend future research directions for the next stage of H-SEIF to explore the value of systemically applying the combined systems and design practices in the concept phase of high-tech innovations utilizing big data. Examples of value creation in industrial applications utilizing big data are supporting management and control of maritime fleets, presenting information supporting critical decision-making in high-risk operations such as offshore drilling, and enhancing situational awareness for onshore command centers in autonomous vessel operations.

The initial evaluation of the proposed practices in this thesis reveals benefits and concerns in an industrial application. We found ways to support the exchange of knowledge and perspectives that enable rapid learning of systems knowledge and application of that knowledge in innovative systems concepts. However, we also experienced skepticism to new ways of working and a lack of skills among systems engineers to achieve the capabilities such as skills for facilitation and visualization. Developing practical ways of working that combine systems and design practices is a balancing act between two worlds, and clearly, more research is needed to identify the value this combination may provide for Systems Engineering. We see the need for further research to validate the identified capabilities and propose using the success criteria for future validation.

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Article 1

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Early Validation of User Needs in Concept Development; a Case Study in an Innovation-Oriented Consultancy

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Abstract. An innovation consultancy applies human-centered methods to explore user needs in the early phase of concept development. This paper compares methods applied by the consultancy with theory from the body of knowledge within Design Thinking and Systems Engineering. The basis for this research is observations and interviews for three specific cases for three different customers. This paper presents criteria and impacting factors on how effective the innovation consultancy performs early validation of user needs. A properly planned co-creation session with the customer is the core. Using a key driver graph we found the main impacting factors to be research on user needs, technology and market trends, techniques used for analyzing the problem and solution domain, selection of participants, and the competence of the facilitator. We conclude that in these three cases the methods are effective in communicating innovative ideas and concepts with the purpose of early validation of user needs.

Keywords: Human Centered Design · Systems Engineering · Early Validation · Design Thinking · User Needs · Innovation · Co-creation Sessions

1 Introduction

This paper presents a case study in an innovation-oriented consultancy for early validation of user needs in the concept phase. The innovation consultancy develops concepts, prototypes, and full-scale systems to customers within several domains. Early validation of user needs is essential to avoid costly design changes and to develop systems that fulfill their purpose for humans. Systems Engineering emphasizes the importance of identification of stakeholders, among them the users, and their needs to understand all perspectives related to the system of interest. These user needs must be identified and clearly communicated. A challenge is that the softer human values may lose in a trade-off with the more specific technical requirements.

The following research question is the foundation of this research: *how effective does the innovation consultancy apply the methods for early validation of user needs in the concept phase?*

1.1 Research Methodology

Case studies [1] form the basis for this research within an innovation consultancy providing innovation services to customers within different domains. This research focuses on three specific cases for three different customers. To determine what impacts the effectiveness of the early validation method used by the innovation consultancy, we firstly conduct a literature review on the state of the art of the various early validation methods. Through observations, interviews and discussions with technical engineers and designers, we investigate how the innovation consultancy performs early validation of user needs and why they are doing it this way.

2 State of the Art Early Validation of User Needs

Early validation of user needs is a fundamental concept within Systems Engineering and Design Thinking. A major difference between the approaches is the applied industrial domain. Systems Engineering validates user needs by reviewing user requirements with customers and/or users [2]. Furthermore, the Systems Engineering approach applies ConOps [2] and/or OpsCon [3] to describe the operational concept of a system using scenarios. Traditionally, ConOps and OpsCon are highly textual-based methods originating from the defense industry. Several variants of the ConOps use less text and are less time consuming, such as agile ConOps [6] and illustrative ConOps [4]. Stakeholder analysis is applied for early validation in the Systems Engineering approach [5].

Storytelling and narratives [6] are early validation methods of user needs applied within Systems Architecting and agile forms of Systems Engineering, but also common in consumer-, IT-, and health care domain. These methods are used to understand the context of use. Conceptual modeling is another early validation method commonly applied within Systems Architecting [7]. This method provides an early validation of the most relevant quality attributes at customer/operational level.

Rapid prototyping is typically used within Design Thinking [8], [9]. This provides quick and dirty validation of ideas using low-cost equipment in rapid iterations. Design Thinking is also advocating for releasing prototypes into the market in order to validate user needs at an early stage [10]. Virtual prototyping is another type of early validation method, based on a visual or software model of the system [11].

Business modelling canvas [12], value proposition canvas [13] and the Lean Canvas [14] are techniques used for early validation in business theory among others based on a lean approach. Within the IT and enterprise sector, we find the workflow analysis used for early validation as it provides a systematic way of mapping the use of the system.

3 Early Validation Using Co-Creation Sessions

Based on the state of the art of early validation of user needs, we find existing methods that have proven applicable, and useful in several domains such as defense and aerospace. Based on the innovation consultancy's need for rapid validation in concept phase, we find the traditional early validation methods within Systems Engineering to be time consuming and comprehensive. The innovation consultancy has developed innovation services for early validation of user needs which are heavily inspired by more rapid approaches, such as Design Thinking [8], [9], Systems Architecting [6] and business theory [12], [13].

The innovation consultancy offers co-creation sessions to customers for early validation of user needs for technological product development. Their vision is building the brand of an innovation consultancy that provides product development based on human behavior. Fig. 1 shows the co-creation session with main input and output.

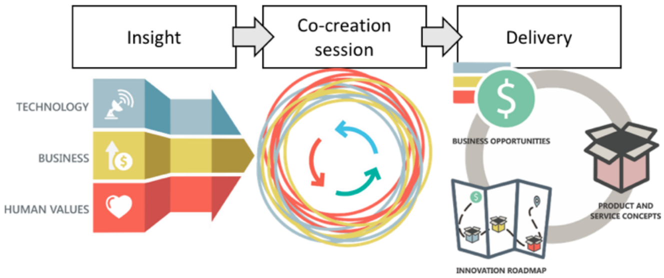

Fig. 1. Co-creation session with input and output

The insight phase on the left side is focusing on the three aspects of innovation; technology, business, and human values. This phase is an important input to the co-creation session, and typically includes stakeholder mapping and analysis, field visits, interviews, research on market trends and enabling technology. The duration of this phase is 1–2 weeks and the consultancy performs it in close communication with the customer.

The co-creation session with the customer is a direct interaction with several stakeholders from the customer and lasts for 1–3 days. The consultancy carefully plans the agenda of the session, choosing techniques from an internal library and adapting to the context and the participants. They select participants based on experience, role and if possible on personality. External stakeholders may participate if the consultancy expects added value from their participation. One or two people from the consultancy facilitate the co-creation session. The session may include other participants from the consultancy as well.

The delivery phase involves mapping and analyzing all collected data produced in the co-creation session. Typically, this phase has a duration of 1–3 weeks and the consultancy performs it. The outcome is refined concepts and a plan for further actions.

Table 1. Co-creation session case profiles

Case no.	Domain	Objective	Participants
1.	Cabin tourism	Innovative cabin resort	7 (customer), 2 (consultancy)
2.	Chemical plant	Increased loading efficiency	8 (customer), 5 (consultancy)
3.	Demolishing plant	Effective and efficient demolishing	18 (customer), 4 (consultancy)

We base our research upon three separate cases within three different domains. Table 1 describes the profiles of each of our cases.

4 Criteria and Impact Factors of Co-Creation Sessions

By using a key driver graph, we derive the criteria for an effective method from the innovation consultancy's perspective. The key drivers provide the objectives of applying the method, which makes them good candidates as criteria for evaluation. We discuss how these factors play a role in achieving the criteria.

The key drivers shown on the left-hand side in Fig. 2 derive from observations and interviews of facilitators and participants of the three separate cases within the innovation consultancy. The key drivers represent the criteria of effectiveness for the early validation of user needs. To realize the key drivers (criteria) the innovation consultancy applies several application processes using the means shown on the right-hand side in Fig. 2.

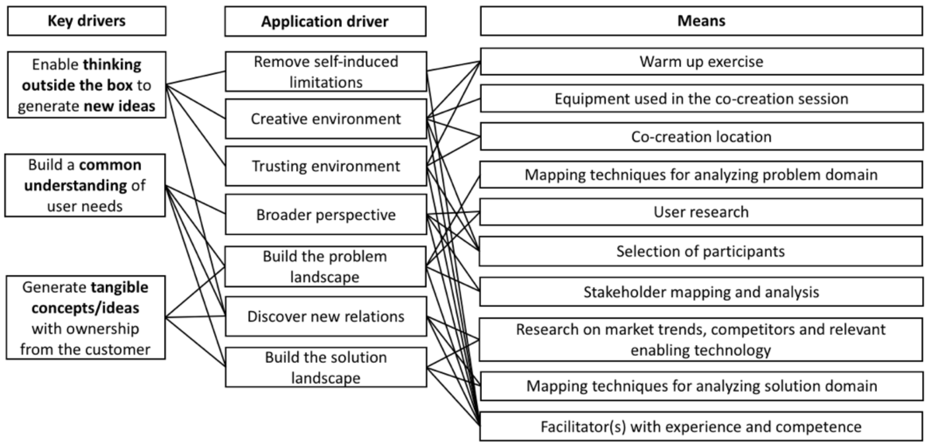

Fig. 2. Key driver graph of the co-creation session

Enable thinking outside the box to generate new ideas is a key driver. The innovation consultancy applies several means to realize this key driver, such as a *warm up exercise* that contribute to the application drivers *remove self-induced limitations* and provide a *creative* and *trusting environment*.

The *selection of participants* for the co-creation session is a mean to a *creative* and *trusting environment*, as well as a *broad perspective* to realize the key drivers *enable thinking outside the box* and *build a common understanding of user needs*.

The means shown on the right-hand side in Fig. 2 are representative of the impact factors on the effectiveness of the early validation method. An important part of co-creation sessions is *playful (warm up) exercises* aiming to prime the participants with some subconscious information and set the mood to achieve the session's goals. Examples of these exercises include describing one's superpowers as a superhero, explaining why one has gotten an imaginary gift from another or a physical activity that require negotiating a team strategy to win a competition. These types of tasks function as an exercise to *remove self-induced limitations*, open for *creativity* and create a *trust* between the participants.

The *equipment and the room(s)* used in the co-creation session need to support more practical issues like a large wall for mapping activities, sticky notes in diverse colors, drawing ink instead of common pens to minimize use of word on sticky notes (be specific and easier to read for all), rapid prototype equipment like tape, carton, and paint.

The *location of the co-creation session* is also important to remove the participants from their everyday controlled working environment. This creates space for wonder, curiosity, and play.

Building the problem landscape takes place in the first phase of the co-creation session and *building the solution landscapes* takes part in the later phase. The innovation consultancy has experience with various techniques for this purpose, such as user research based on interaction and interviews with users in their operational context (part of insight phase prior to co-creation session), canvas for eliciting user needs, mapping current and better view of the situation on a timeline, and canvas for understanding pains and gains. When the focus is turning more towards the solution landscape, the innovation consultancy applies techniques for ideation, evaluation, and selection of ideas. These techniques include categorization of ideas based on effort, tangible value (revenue) intangible value (brand awareness or customer loyalty), selecting ideas by voting with stickers etc.

Another impact factor of the co-creation session is the *selection of participants*. To provide a trusting and creative environment, as well as a broad perspective, the facilitator has to consider the group dynamic needs based on personality, experience, and competence carefully.

Doing business on providing innovation services like the co-creation session, also require *facilitators with competence and experience* to guide, inspire and lead the participants through the session.

5 Discussion and Conclusion

This paper explores criteria for an effective early validation of user needs from an innovation consultancy perspective. Three specific cases in three different domains are the basis for this study.

As part of the insight phase for the co-creation session, the innovation consultancy performs user research by interviewing and interacting with users in their operational context. This is well aligned with the empathize phase in Design Thinking [8] and stakeholder analysis in Systems Engineering [5]. The insight phase also includes research on enabling technology, market trends and competitors, as we find in business model theory [12]. During the co-creation session, the innovation consultancy performs exercises for removing self-induced limitations and makes use of different techniques to analyzing the problem and solution domain, such as considering pains and gains. These methods are familiar in both Design Thinking [8], [9], Systems Architecting [7] and business theory [13]. Playful (warm up) exercises are however more common in Design Thinking than in Systems Architecting.

By using a key driver graph, we derived criteria and impact factors of the effectiveness of the early validation method applied by the innovation consultancy. The derived criteria are: *think outside the box to generate new ideas*, *build common understanding of user needs*, and *generate tangible concepts with ownership from the customer*. The main impact factors are: *research on user needs, technology and market trends*, techniques used for *analyzing the problem and solution domain*, *selection of participants*, and the *competence of the facilitator*. We conclude that in these three cases the methods are effective in communicating innovative ideas and concepts with the purpose of early validation of user needs.

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Article 2

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Systems Thinking for Early Validation of User Needs in the Front End of Innovation; a Case Study in an Offshore SoS

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***Abstract*—This paper focuses on applying Systems Thinking for early validation of user needs in the front end of innovation for extending an offshore SoS with renewable energy. A high degree of uncertainty and ambiguity characterizes this early phase. Early validation of user needs is assumed to be a key for successful value creation in the early phase development of new systems. The user needs can be difficult to understand and subject to change due to the ambiguous nature of the innovation process. Systems Thinking is a mindset that increases understanding of the system´s context and behavior; it helps identifying possible leverage points. This paper applies Systems Thinking methodology in a real case for an industrial project adding renewable energy to offshore installations. We developed in this research graphical presentations to communicate system openness and user needs for the operational phase of the system. The graphical presentations were tested out on stakeholders. We found the Systems Thinking methodology and the graphical presentations to be helpful tools for successful stakeholder communication with the purpose of early validation of user needs.**

***Keywords*— early validation, user needs, Systems Thinking, renewable energy, front end of innovation, early phase systems engineering**

I. Introduction

A. The Front End of Innovation

This paper focuses on the application of Systems Thinking to perform validation of user needs in the front end of innovation. The front end of innovation is the very first phase of a new product development [1], or the early phase of systems engineering [2]. This early phase is recognized as relevant for the success of the innovation and presents a great opportunity for the overall innovation process [3], [4].

In the front end of innovation, the system boundaries are usually unclear, and the uncertainty is high. There are several different variables acting upon the system that might change the concept and the path forward. Salado and Nilchiani [5] performed a literature review within Systems Thinking and confirmed the suitability of Systems Thinking on socio-technical problems to find effective solutions. Kjørstad and Falk "unpublished" [6] investigated the potential for a Systems Thinking mindset for effective decision-making in the front end of innovation in the offshore sector. Due to the high degree of complexity represented by the harsh and inaccessible offshore environment and the human interaction with the systems, Kjørstad et al. found the Systems Thinking mindset and the Cynefin framework [7] to be probable solutions to increase the innovation ability in this sector.

B. Early Validation of User Needs

According to Design Thinking, understanding *user needs is just as important as the technology and business aspects* in order to develop innovative solutions [8]. Kelley and Kelley describe innovation as the perfect balance of business, technology and human, as shown in Fig. 1 [9] p. 19.

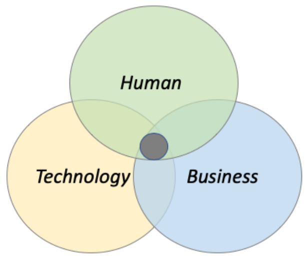

Fig. 1. The sweet spot of innovation [9]

Early phases of innovation tend to focus on business and enabling technology. The main concern is often to enable further funding of the project. The importance of validation of user needs, represented by the green "human" circle, is in risk of being neglected or found as not important in this phase.

There are several approaches for early validation of user needs. Kjørstad et al. [10] presented an overview of various early validation methods that have proven effective within their domains, such as stakeholder analyses and ConOps applied in traditional systems engineering, conceptual modelling applied in systems architecting, empathize with users through user research as advocated by Design Thinking, and the Business Model Canvas and Lean Canvas applied in business theory.

C. The Renewable Energy Addition of an Offshore SoS

This research is performed within a leading global company who provides subsea systems and installation services to the offshore oil and gas domain. Specifically, within a part of the company located in Norway that has provided subsea production systems to offshore oil and gas operators for the last 40 years.

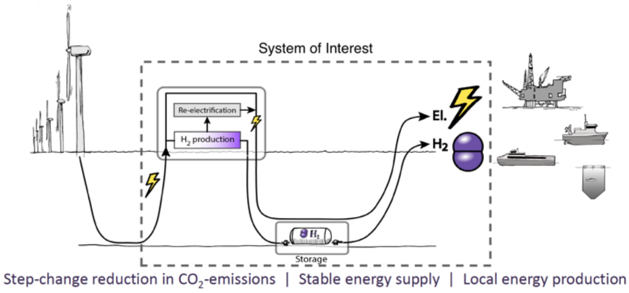

Fig. 2. The Deep Purple system and its context

The company has an increasing focus on developing sustainable solutions for their domain. They have initiated a front-end innovation project to develop a *renewable energy system for offshore consumers*. The project aims to supply stable CO_2-free energy to consumers. Fig. 2 shows the renewable system, named Deep Purple, and its context.

Deep Purple captures excess power from off grid wind farms and temporarily stores energy in the form of hydrogen subsea. The hydrogen can be transferred directly by pipeline to consumers offshore or onshore or converted to electricity for consumers nearby.

The company is in needs of a rapid approach to analyze the stakeholders of Deep Purple and their needs, and methods to cope with the complexity represented by the uncertainties and ambiguities in this early phase of the project. In this paper, we pursue *the applicability of the Systems Thinking methodology as a potential early validation method of user needs in the front end of innovation* for the offshore System of Systems (SoS).

Firstly, we present the research method. Then we present the current challenges and opportunities for the front-end innovation project. Further we apply the Systems Thinking methodology on the case and identify system boundaries, stakeholders and interests, graphical presentations and possible leverage points. Finally, we evaluate the results, and present our conclusions and future research.

II. Research Method

The basis for this research is industry-as-laboratory, a strategy often applied in research on systems engineering [11]. We have applied qualitative research methods using observations and informal interviews within a longitudinal time horizon. This paper connects the observed challenges to the literature review and proposes the Systems Thinking methodology as a possible solution.

III. Challenges and Opportunities

The company requires a mix of known and unknown knowledge in technology and market for the front-end innovation project. The user needs are unknown, while the consumer of hydrogen can vary in domain and location. The company focus is currently to *gain knowledge of the enabling technology and investigate potential market opportunities*. In this paper, we focus on the concept for providing energy to an offshore oil and gas production platform on the Norwegian Continental Shelf (NCS).

The Norwegian Research Council and the company are funding the project. The priority of the company is to *prove the business case* to enable commercialization. The company perceives the *total cost of ownership*, consisting of the operational expenditures (OPEX) and capital expenditures (CAPEX), as the main drivers for a potential customer.

The Norwegian Government has a high focus on initiatives for reducing CO_2 emissions in the offshore oil and gas domain. They establish *funding opportunities* to support such initiatives, and they are stimulating field operators to reduce CO_2 emissions by regulating a *CO_2 tax*. Due to the Norwegian Government's responsibility towards the Paris Agreement, the CO_2 tax will probably rise in the near future.

IV. The Systems Thinking Methodology Applied

Systems thinkers view most systems as living (open) systems, moving towards order and complexity [12]. The founder of general systems theory, Ludwig von Bertalanffy, introduced the terminology and world view in the 1940s [13]. Systems theory is a scientific approach to understanding all types of systems, from biological and ecological systems to conceptual systems.

Systems thinkers claim systems can only be understood in context of their environment. The system context is one of the main principles of a system's behavior, and provides an understanding of the openness of the system [12]. The importance of understanding the system's context is also a fundamental principle in systems engineering [2].

A. System Boundaries

Deep Purple can be viewed as a living (open) system. There are three variables that come to play when we investigate an open system [12]: the *controllable variables*, the *uncontrollable variables* we can *influence* and the uncontrollable variables we cannot influence but will have to *appreciate*.

Fig. 3 shows the openness of Deep Purple. We identified as influencing variables within the system's environment: potential customers (such as the field operator), the offshore wind park operator, the authorities that

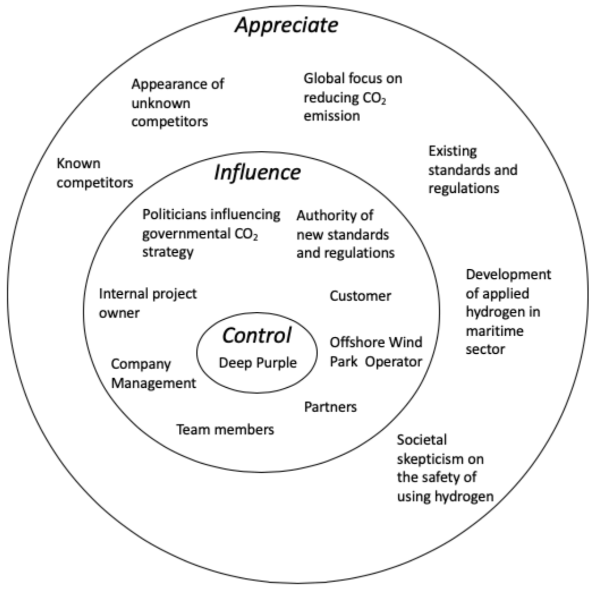

Fig. 3. Context diagram of Deep Purple

develop new standards and regulations that may apply for hydrogen production offshore, potential partners of relevant technology (such as fuels cells and electrolyzers), the project team, politicians that act upon the governmental strategies, the internal project owner within the company, and company management.

Further out in Deep Purple's environment we find the uncontrollable variables that the project can only appreciate. The source to the original idea of Deep Purple: the global focus on reducing CO_2 emissions due to the challenge of global warming is one of these variables. The hydrogen market offshore is under development and get higher and higher focus within the industry. The probability of emergence of unknown competitors is high.

Other uncontrollable variables relevant for Deep Purple are existing standards and regulations for operations on the NCS (including wind farm operation and the use and storage of hydrogen). The level of maturity of applied hydrogen in the maritime sector, as well as the hydrogen grid onshore, is also important variables that may affect Deep Purple. However, the company probably cannot influence it.

Social skepticisms on the safety related to use and storage of hydrogen is another challenge for Deep Purple. Unfortunately, hydrogen has a bad reputation in the society due to accidents like the Hindenburg disaster. This skepticism needs attention when considering the use and social acceptance of Deep Purple. Communication of safe use and storage of hydrogen in Deep Purple, the risks and benefits, is probably a good approach towards the society to mitigate this skepticism.

To get a further understanding of the front-end innovation project's behavior, we need to understand *what* the stakeholders do, *how* they do it and most importantly *why*.

B. Stakeholders and their Interests

Stakeholders in the influence sphere will need to take the best choices for the front-end project to drive it forward. Understanding the stakeholder's interests, why they do what they do, are of high importance in order to affect the choices they make. After all: "*The world is not run by those who are right. It is run by those who can convince others they are right*" [12] p37.

The field operators on the NCS are encouraged by the Norwegian Government to reduce CO_2 emissions and provide CO_2-free alternatives for oil and gas production[1]. Table 1 shows the main stakeholders for the Deep Purple project and their interests.

The Norwegian Government has a high focus on CO_2 reduction, especially within the oil and gas domain. Influencing the right *politicians* may help to find collaboration partners and be beneficial for further funding of Deep Purple.

Table 1. Stakeholders and their interests

Stakeholder	***Interests (why)***
Politicians influencing the governmental CO_2 strategy	Oil and gas actors contributing to CO_2 reduction (support the Paris Agreement)
Internal project owner	Proven business case (to enable commercialization)
Company Management	Customer satisfaction and sustainable solutions (to win more contracts and strengthen reputation)
Team members	Gain knowledge on hydrogen technology and new market opportunities (expand experience and contribute to sustainable solutions)
Authority of new standards and regulations	Safe and sustainable use of hydrogen technology offshore
Partners	Collaborate with enabling actors in the industry (to enter new market opportunities)
Offshore wind farm operator	High availability of the offshore wind park (provide the power that the consumer need at the time they need it) Sustainable solutions (to be in accordance with its main objective)
Customer (field operator)	Total Cost of Ownership (to stay compatible) CO_2-free stable energy to their installation (safe operation without CO_2 emission fee with high availability)

The *internal project owner* wants to prove the business case of Deep Purple, to enable commercialization. Relating user needs to the business case of Deep Purple may help to convince both internal project owner and potential customers of the impact that Deep Purple has on the total cost of ownership. *Company management* is concerned with company profit (getting more contracts) and strengthening the company reputation on sustainability. The main purpose of Deep Purple is to provide a more sustainable solution. A clear communication of how Deep Purple works and how this relates to total cost of ownership may help to strengthen the project's position at top management.

The project manager handpicked *team members* for the project. The interest of each of the team members probably varies, however they all share a common interest in gaining knowledge on sustainable solutions. The possibility of gaining knowledge and experience during the front-end innovation project might provide them with valuable competence for future projects within a potential new market domain for the company. Handpicking team members is probably worth the effort, to ensure that the project has the relevant expertise and the interests within this new market segment.

Regulation authorities strive for safe and sustainable operation of hydrogen in the maritime and offshore domain. Looking towards existing standards and regulations, and continuous communication with regulation authorities may help to find the operational challenges and opportunities provided by future regulations. Sustainable innovations in this

[1] It might seem like a contradiction that oil and gas operators are striving to reduce CO_2 emissions, when their main purpose is to produce oil and gas that will indirectly lead to more CO_2 emissions. The Norwegian Government is still relying on oil and gas production, and this will probably be the case for many years to come. However, reducing CO_2 emissions from the production facility itself will contribute to a more sustainable oil and gas production.

domain may as well lead to adjustment of existing standards and regulations and form the future ones.

Providers of fuels cells and electrolyzers will probably be interested in *collaboration and partnership* with the front-end project, as they might see this as a possibility to enter a new market. Such providers of typical "green solutions" will probably see the benefit of adding their technology and experience into the oil and gas domain due to the governmental focus on reducing CO_2 emissions offshore.

Throughout the year, the offshore wind will vary and hence provides a variable and unpredictable source of power to the production platform. The main interest for the *wind farm operator* is to provide power to the consumer with high predictability. Being a provider of renewable energy, they should also be interested in providing sustainable solutions to the energy consumer.

The production platform, owned by the *field operator*, is the consumer of the off-grid power. Their interest is access to stable CO_2-free power for optimal oil and gas production. The field operator's interest is to operate the production platform according to relevant rules and regulations in a safe manner, and the total cost of ownership for Deep Purple.

C. Graphical Presentation of the User Needs

Utilizing Systems Thinking tools, such as a systemigram, may benefit the project team with the purpose of communicating user needs towards stakeholders. The systemigram is a graphical presentation of thoughts intended to be used for communication [14]. Salado and Nilchiani [5] stated that the tool is effective for identification of stakeholders within engineering teams developing earth observation space systems. Sauser et al. [15] also stated the effectiveness of the systemigram when sharing different stakeholder perspectives and thoughts in development of a definition for resilience in maritime homeland security.

Fig. 4 shows a systemigram of Deep Purple. The figure aims to inform how the user needs relate to the purpose of the Deep Purple. The systemigram elements are categorized into the main focus elements in the sweet spot of innovation (Fig. 1); human (users and their needs), technology and business.

In the upper left corner of the figure, we find the system of interest: Deep Purple. In the lower right corner, we find the main goal of Deep Purple that is to reduce CO_2 emissions. The mainstream (bold font) describes the main purpose of Deep Purple: *Utilize new technology in combination with existing technology to produce off grid stable CO_2-free power to achieve a reduction of CO_2 emissions.*

The oil and gas platform are the operational user of Deep Purple, that needs reliable access to off grid stable CO_2-free power for optimal oil and gas production. The field operator owns the oil and gas platform and is a potential customer that needs solutions for reducing CO_2 emissions. The Norwegian Governments is in need of CO_2-free solutions, and the Paris Agreement relies upon Governments to initiate incentives to achieve reduction of CO_2 emissions.

The benefit for the field operator is continuous access to stable CO_2-free power, independent of variations in offshore wind. The hydrogen subsea storage will reduce the size of the wind farm, which affects the total cost of ownership for the field operator positively. The funding possibilities and CO_2 tax set by the Norwegian Government will also affect total cost of ownership positively.

It should be noted that Fig. 4 does not visualize the usage of Deep Purple for the life cycle phases related to installation, maintenance, replacement nor retirement.

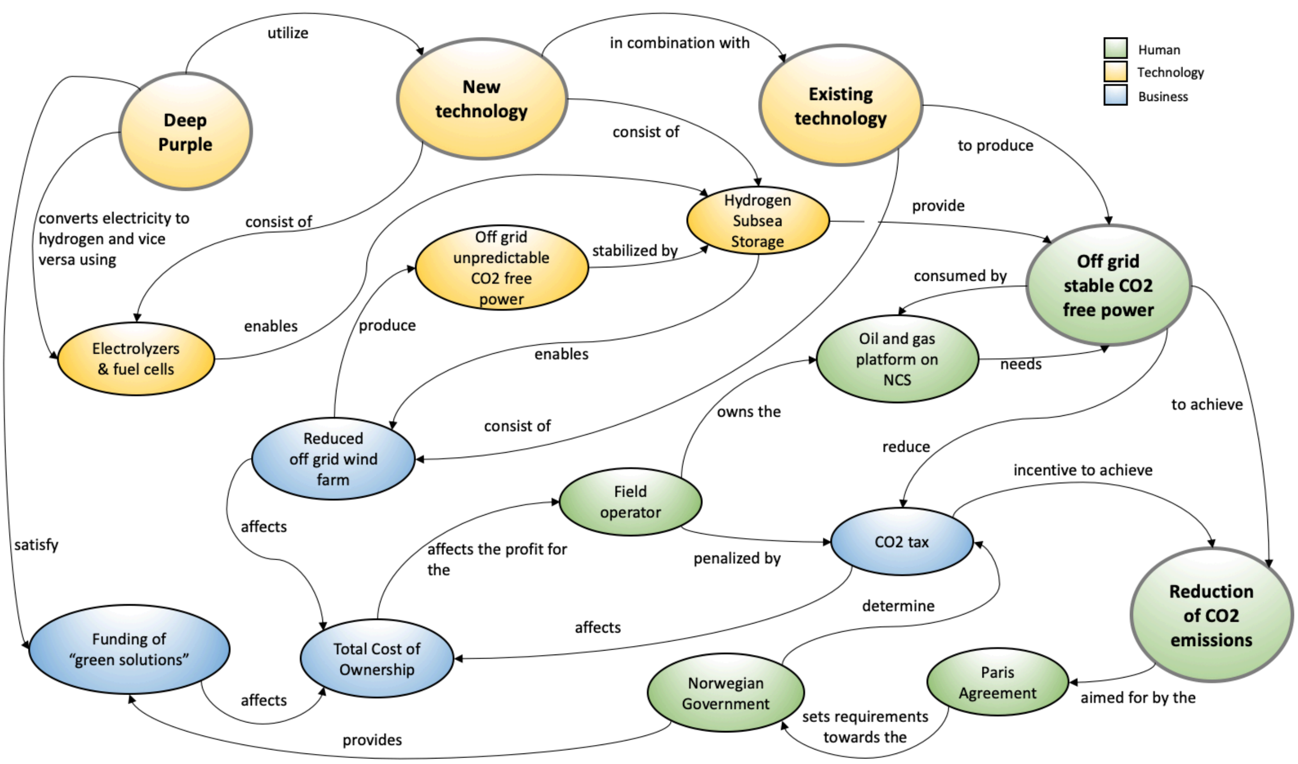

Fig. 4. Systemigram of Deep Purple

D. Possible Leverage Points

The Paris Agreement aims to reduce CO_2 emissions to prevent global warming. The systemigram in Fig. 4 focuses on reduction of CO_2 emissions as the main purpose of Deep Purple, driven by the Paris Agreement. The benefit of Deep Purple concerning total cost of ownership for the field operator depends mainly on the CO_2 tax and funding possibilities given to "green solutions" provided by the Norwegian Government. This indicates that *the future changes in the Norwegian Government's CO_2 strategy will have a large impact on the business case for Deep Purple*

Another interesting force that acts upon the system is the future of oil and gas production. The systemigram focuses on application of Deep Purple towards an offshore production platform. The global focus on reducing the use of fossil fuels is high, and renewable energy sources are a hot topic these days. The company is a provider of subsea systems and installations services to the oil and gas domain. The *future of the oil and gas domain will affect the application of Deep Purple*, as well as the core business of the company.

The systemigram provides information on how the production platform relates to Deep Purple and the benefit it gets from this collaboration. Off grid wind farm as a power source to production platforms is a new concept in development by field operators today. If the field operator owns the wind farm, the systemigram shows how total cost of ownership help to meet the user needs of the field operator. If the field operator does not own the wind farm, *the benefit of Deep Purple for the wind farm is unclear*.

At this point in time, the project team has not yet had the possibility to perform user research of the external stakeholders. As the project progresses and establishes collaboration with external stakeholders, the next step will be to *investigate the user needs of the various stakeholders further to validate the assumptions made so far*.

V. Evaluation

A. Developing the Graphical Presentations

The researchers developed the graphical presentations (Fig. 3, Fig. 4) based on discussions with the other team members. The development was an iterative process. The context diagram and stakeholder table were established in a few hours. The systemigram took approximately two weeks to develop and required several iterations to mature and reach a satisfactory level.

We found it challenging to develop a systemigram given the design rules presented in [14]. This might be due to several reasons. There were several views of the system that we unsuccessfully tried to include, such as the role of competing and existing technology (cable to shore and gas turbines) and how this relates to Deep Purple. We also found it difficult to include other life cycle phases than the operational life cycle phases, such as installation, maintenance, replacement and retirement. We found that by including too many relations into the systemigram, we failed to bring a clear message through. By selecting a set of relations and views, we were able to provide a message with a clearer meaning.

B. Testing of the Graphical Presentation

The project manager tested out the graphical presentations in two separate meetings with external stakeholders. The test was performed with a black & white version of the systemigram, without categorizing into humans, technology and business. The external stakeholders were unfamiliar with the Deep Purple system prior to the meeting. One meeting was with a potential collaboration partner of fuel cells and electrolyzers systems. The other meeting was with a consultancy for business strategy. In both meetings, the graphical presentations got good feedback, especially the systemigram. The meeting participants were unknown with systemigrams beforehand and found the systemigram to be fascinating and informative. The project manager also found the systemigram to enable an intuitive and systematic communication of the purpose of Deep Purple. The internal concept report to describe the purpose of Deep Purple for the offshore oil and gas platform on the NCS applied the systemigram.

VI. Conclusion and Future Research

In this paper, we pursued *the applicability of the Systems Thinking methodology as a potential early validation method of user needs* in the front end of innovation for a real case in the offshore SoS.

The case is adding an off-grid renewably energy system for offshore consumers, called Deep Purple. The industrial front-end innovation project is a sustainable initiative for a global provider of subsea systems and installation services in the oil and gas domain. The researchers have been part of the industrial project team. They applied Systems Thinking methodology, developed context diagram and systemigram of Deep Purple and tested it out on external stakeholders.

We found it challenging and time-consuming to develop a systemigram with a clear message and according to the design rules given in [14]. The systemigram shows the operational view of the system, however we were unable to show other important life cycle phases for the user, such as installation and maintenance. Adding more systemigrams showing the missing relations and views can most likely solve this.

Analyzing the openness of Deep Purple using the context diagram and the stakeholder interest table indicates to be a low-effort and powerful tool to analyze stakeholders and their needs. Developing a systemigram indicate to be a slower but helpful tool to further understand the complexity of Deep Purple and its context. The systemigram also indicates to be a good commination tool towards external stakeholders to communicate the purpose of Deep Purple.

The Systems Thinking methodology indicates to be helpful in the early phase of systems engineering to provide understanding of stakeholder needs and manage complexity. Further research is needed to conclude on how effective it is for early validation of user needs in the front end of innovation.

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Article 3

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Exploring a co-creative problem solving toolbox in the context of Norwegian high-tech industry

Marianne Kjørstad, Kristin Falk, and Gerrit Muller

***Abstract*—Norwegian high-tech industries face a rapidly changing market need. Staying ahead of competitors and developing significant innovative solutions are essential for business value. Systems engineering has proven to be an effective approach for developing technical (hard) systems. People, organizations, and technical functionality contribute to an increasing complexity in today's high-tech systems. This makes the traditional systems engineering approach insufficient for innovation in a socio-technical context. This paper looks towards systems architecting, systems oriented design, and participatory design for collaborative and creative ways of working to support systems engineers in developing significant innovations. We explore a rich toolbox and the outline of a new methodology for such co-creative problem solving. Firstly, we identify industry needs for the new methodology and derive success criteria for the toolbox embodied in the new methodology. Through ten industry cases within Norwegian high-tech industries, we analyze and discuss the toolbox composed of methods and tools for early exploration, validation, and knowledge transfer in the concept phase. Finally, we provide examples on how the toolbox supports the industry needs and outline the new methodology.**

***Index Terms*—Creative problem solving, concept exploration, early validation, significant innovation, socio-technical systems**

I. Introduction

NORWEGIAN high-tech industries face a rapidly changing market need. Staying ahead of competitors and developing innovative solutions are essential for business value. Systems engineering [1] has proven to be an effective approach for developing technical (hard) systems. People, organizations, and technical functionality contribute to an increasing complexity in today's high-tech systems. Checkland [2] described such socio-technical problems as *real world problems*, and introduced the term *soft systems* to address this. Innovating in a context of soft systems using a traditional systems engineering approach has proven challenging [3]–[9].

Previous research has discussed the potential of combining design- and systems approaches [5]–[8]. However, we have not found literature that focuses on the industrial challenges for systems engineers to innovate in a soft systems context, nor the main influencing factors to address for the industry to overcome these challenges. To support systems engineers to innovate in a soft systems context, we explore collaborative and creative ways of working through a *co-creative problem solving toolbox*. The naming is referring to the act of collective creativity (co-creation) typical in participatory design [10]. In this paper we define *co-creation* using the description by Sanders, and Sanders and Stappers [11], [12]. They described co-creation in the design development process as co-design, referring to the collective creativity of designers and non-designers (such as users or customers) creating a new product or process.

Seeking to inspire systems engineers to apply more collaborative and creative ways of working than the traditional systems engineering approach offers, this paper provides our experiences using the toolbox and outlines a new methodology. The new methodology aims to support systems engineers to cope better with the complexity of soft systems to develop *significant innovations* to rapidly changing market needs. To define what we mean about significant innovation we refer to Muller [13]. Muller differentiated between incremental and significant innovation in mature companies and described the latter as "*solutions beyond the ordinary*"[1]. According to Muller, mature companies often focus on consolidation and incremental innovation to grow, while significant innovation is much harder to create.

We have conducted research through a collaborative research project including four Norwegian high-tech companies and two academic partners. The academic partners are within the field of systems engineering and systems oriented design. The companies provide innovation services and full-scale systems for the global ocean space, such as service vessels, expedition vessels, subsea systems, and off grid renewable energy systems. Through ten industry cases within the companies, we explore a rich toolbox embodied in the new methodology. In this paper, we aim to answer the following research questions:

What are the industry needs for a new methodology to innovate in a soft systems context? (Section V)

How does the toolbox address the industry needs? (Section VII)

What may be the outline of the new methodology? (Section VIII)

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[1] This terminology is inspired by the Boderc research project conducted through the Embedded Systems Institute in Eindhoven, the Netherlands [60].

By answering these questions, we contribute to the body of knowledge in three ways. Firstly, identifying the industry needs for a new methodology will guide the industry in the main influencing factors to innovate in a soft systems context. Secondly, analyzing how the toolbox addresses these needs provides a better understanding on how to cope with current challenges in the industry. Finally, identifying the outline of the new methodology will provide a good foundation for ongoing research on realization and evaluation of a new methodology.

The following two sections provide background literature on the addressed challenges and relevant literature for the toolbox. Next, we present the research design. Further, we describe the results including the research on industry needs and industry cases on the toolbox. At last, we analyze the toolbox and discuss the way towards the new methodology, before we conclude on the research questions.

II. Background

General Systems Theory developed by Bertalanffy in the 1940s has shown to provide a good basis for a general system framework in recent literature [14]. Bertalanffy [15] described systems theory as a scientific approach to understand systems in general, from biological systems to conceptual systems. Gharajedaghi [16] built on systems theory and characterized a system's behavior using the five principles of openness, purposefulness, multidimensionality, emergent property, and counterintuitivity. To define problems and develop solutions, he emphasized the importance of viewing systems through these principles. He stated that *"no problem or solution is valid free of context"* [16, p. 31]. The importance of a systems thinking mindset in engineering to solve real world problems is well documented in literature, such as [2], [14].

The lack of soft consideration in systems engineering [1] has been a topic for decades. Peter Checkland described the "*failure of systems engineering"* and the following development of the *soft systems methodology (SSM)* in the early 70s [3, p. A35]. Checkland emphasized the need to consider the political aspects of human activities to make changes in the real world that are both feasible and desirable. The main developers of SSM are Checkland, and Wilson. They have published a fair amount of literature on SSM and how it has evolved over the years [2], [3], [17]–[19].

Jackson provided a thorough overview of major systems approaches including SSM in [20]. He defined systems engineering as *hard systems thinking*. He recognized systems engineering as a well-proven approach coping with technical complexity. However, he emphasized the need to look towards other systems approaches for considering various forms of complexity, such as process, structural, political, people, and organizational complexity. Jackson called this *critical system thinking* with the purpose of better managing complexity.

Wade, Hoffenson, and Gerardo [5] discussed strength and weaknesses of major paradigms for designing complex systems. Their discussion included design thinking, systems thinking, systemic design, engineering design, and systems engineering. Wade *et al.* found traditional systems engineering as weaker in the concept phase compared to systems thinking, design thinking and systemic design. They proposed a unified approach combining the strengths of the major paradigms into a new *systemic design engineering*. A pilot of such a curriculum combining elements from systems thinking, design thinking and systems engineering in education has been taught at the Stevens Institute of Technology with promising results [21].

The need to explore a combined approach of design thinking and systems thinking into a new framework or methodology has been proposed in recent literature [5]–[8]. A combined systems and design methodology is assumed to better cope with *ill-defined problems* in the early concept phase with the purpose of developing more innovative solutions. Rittel and Webber [22] introduced the term *wicked problems* in the early 70ties to describe such ill-defined problems. Wicked problems are challenging problems with no optimal solutions, and a focus area in design when developing societal systems. Such systems are overly complex, and demand a different problem solving approach than for hard systems [5]–[8].

The need for informal ways of working to support exploration and context understanding in the concept phase is emphasized by Muller [23]. Muller further described the importance of managing different viewpoints to gain knowledge of multiple perspectives. Thorough understanding of stakeholder perspectives and needs are essential to design *systems fit for purpose* within a *business context* [23]. Muller described this as systems architecting. Systems architecting as a term is not that well accounted for within the literature on systems approaches. Jackson did not mention systems architecting in his overview of major systems approaches [20]. Emer, Bryan, Wilkinson *et al.* [24] found six different perspectives on systems architecting when interviewing systems architecting practitioners. In this paper, we view systems architecting as informal ways of working, complimentary to formal architecting frameworks. From this view, systems architecting presents a systems approach that can supplement the traditional systems engineering to innovate in a soft systems context.

III. Literature Review

This section reviews the literature on the methods and tools that has formed the co-creative problem solving toolbox. We look towards the field of *systems architecting, systems thinking, design thinking, participatory design,* and *systems oriented design* to explore a toolbox fit for the industrial context and industrial need in this research project.

As part of the systems architect's toolbox, Muller proposed an *illustrative concept of operations* (ConOps) [25]. Compared to the traditional ConOps [1], an illustrative ConOps is a visual representation of the sequence of operation of the concept(s), usually captured in an A3. Illustrative ConOps can be used for early validation of concepts in communication towards stakeholders. Solli and Muller [26] applied illustrative ConOps in the Norwegian subsea industry. They found that illustrative ConOps resulted in prompt responses from systems engineers on various concepts and operations, expressing concerns as well as curiosity about the operational steps.

Jensen, Muller and Balfour [27] proposed the usage of an *interactive knowledge architecture* (IKA) for knowledge sharing of the problem domain in the concept phase. They found a desirable knowledge base to work well for knowledge transfer of the problem domain between systems engineers and customers. A mutual understanding of the problem domain in the concept phase is essential for early validation to avoid late and costly design changes.

Inspired by Checkland's [2] way of visualizing systems, Boardman and Sauser developed a technique for visualizing *"readable"* systemic diagrams that capture concepts through systems thinking [28]. They called this technique *systemigram* and used it to communicate and confirm strategic intent. Boardman *et al.* described systemigram as a complement to the richness of prose, and due to its easy readability would reach out to more people enabling a greater shared understanding. Blair, Boardman, and Sauser [29] proposed using systemigram as a storyboard for stakeholder communication. Cloutier, Sauser, Bone, and Taylor [30] proposed using it for capturing knowledge about problems, while Squires, Pyster, Sauser *et al.* [31] applied systemigram to communicate a project's value proposition.

Design thinking was defined by Schön [32] in the early 1980s, and further theorized by others such as Rowe, Cross, Nelson, and Stolterman [33]–[36]. Contemporary design thinking as practiced by the Innovation Design Engineering Organization (IDEO) from the early 2000s, focuses on emphasizing with users to understand the unmet need and develop systems that enhance user experience [37]. Kelley and Kelley [38] highlighted the strong link between creativity and innovation, and described creativity as a mindset that can be trained and used to find new solutions. IDEO advocates such a mindset in a human-centered approach towards innovative solutions. Not only in design and engineering to develop more desirable products and systems, but also in management and business aiming for more creative people and organizations [39]. Inspired by design thinking, Pinto, Falk, and Kjørstad [40] proposed *visual canvases* to develop systems that are desirable, feasible and viable. Visual canvases are structured templates using visualizations to emphasize with users and extract *human values* in stakeholder analysis. In this way, it can be used for early validation of user needs in the concept phase.

Björgvinsson, Ehn, and Hillgren [41] discussed the design thinking approach as presented by IDEO, and claimed that this *"sounds like good old Participatory Design"*. Participatory design as a design practice and theoretical field originates from the 1970s. Sanders *et al.* [12] discussed co-design within the area of participatory design. They described co-design as *"the creativity of designers and people not trained in design working together in the design development process."* Further, they positioned participatory design towards *"user as a partner"*, and user-centered design towards *"user as a subject"* focus. This indicates a switch from the design thinking mindset towards a more collaborative approach. Sanders *et al*. pointed to participatory design as a fitting approach in the front end of development. They claimed that participatory design will enable a better exploration, user- and context understanding in this fuzzy phase. Kjørstad, Falk, Muller, and Pinto [42] proposed the use of *co-creation sessions* for early validation of user needs in the concept phase. Co-creation sessions are carefully planned sessions for concept exploration with customers and third parties, using tools and techniques inspired by design thinking, systems architecting, and business management.

Systems oriented design (SOD) stems from systemic design that has evolved within the design community [43]. SOD holds many similarities to conceptual modelling within systems architecting and SSM. SOD provides a method to cope with complexity using visualization, called *gigamapping* [44]. Gigamapping is used to explore complex problems and interrelations, using large sheet of papers on walls or tables and pens. Gigamapping can be used to explore freely or more structured, such as using a timeline or canvas. Structured gigamapping is typically to make a customer journey. Gigamapping is based on design practice and tacit knowledge that has evolved over time. The tacit knowledge has in recent years been captured in publications such as by Sevaldson [45]–[47]. Sevaldson [47] highlighted the main benefit from gigamapping to be sense sharing between stakeholders that co-create the gigamap.

IV. Research Design

This research is based on *action research* [48]. Action research focuses on acquiring knowledge by entering a real world situation with the intention of improving it. We find this approach as appropriate for exploring the co-creative problem solving toolbox and the outline of the new methodology. It allows us to get a thorough understanding of the industry needs and potential solutions within the context of the high-tech companies.

A. Research Methods

Using *informal interviews*, *focus groups* and *surveys* towards the industry partners, we identified the industry needs for a new methodology and derived success criteria to evaluate the toolbox. Through analyzing *empirical data* collected from industry cases, we built a problem understanding of the pros and cons of applying the toolbox.

Further, we analyzed the findings to evaluate how the toolbox satisfied the success criteria and outlined the new methodology. Final realization and evaluation of the new methodology is part of ongoing research, aiming to develop an industry guide.

B. Industry Partners

This research project has four industry partners providing innovation services and full-scale systems within the ocean space. Table 1 shows the profiles of the industry partners.

Table 1. Profile of industry partners

Company	Business	Size of company
A	Ship design	medium
B	Innovation consultancy	medium
C	Innovation incubator	small
D	Subsea EPCI supplier	large

Company A is a family-owned company with about 100 years of history designing and building ships, such as service operations and anchor handling vessels. They are well known for providing innovative solutions and have recently expanded into new markets such as expedition vessels. In recent years, they have had a strong focus on strengthening their expertise in systems engineering.

Company B is an innovation consultancy. During the past decade they have been shifting from a traditional engineering consultancy into an innovation consultancy focusing on product development based on human behavior. They have built up a profession based on design thinking tools, co-creation design, as well as systems engineering.

Company C is an innovation incubator, providing innovation services to small and medium-sized enterprises (SME) and start-ups developing high-tech solutions. They have a strong connection to several medium to large high-tech companies, providing the advantage of these connections to their customers. The incubator has a strong focus on value proposition and business models using tools such as the business model canvas [49] towards the start-ups.

Company D is an engineering, procurement, construction, and installation (EPCI) supplier of subsea systems and services with about 40 years of experience supplying reliable systems operating in a rough environment. The EPCI supplier is strong on engineering. The last decade it has in addition strengthened its systems engineering expertise focusing on effective execution.

C. *Industry Cases*

We have done research in ten cases within the industrial partners. This has been a combined effort of five systems engineering master's students and one PhD student. In each case the researchers have engaged with the systems engineers to build a thorough problem understanding and a proper evaluation of the methods and tools in a real-world context. Table 2 shows the profile of the cases.

Table 2. Profile of industry cases

Case no.	Company	Methods and tools	Publication
1	All	Gigamapping	-
2	B	Visual canvas	[40]
3	B	Visual canvas	[50]
4	B	IKA	[27]
5	A	IKA	[51]
6	D	IKA	-
7	D	Systemigram	[52]
8	D	Illustrative ConOps	[53]
9	B	Co-creation sessions	[42]
10	B	Co-creation sessions	[54]

We have published eight of the ten cases as part of the research project. The fifth column provides a reference to this work for readers with specific interests in a more detailed description of each case. For Case 1 and 6, we collected empirical data using *surveys*, *participant observations*, and collection of *benefits and concerns* reported by the participants.

D. *Limitation of research*

In this research, we had no control of the research environment. The cases have been explorative, adapted to the specific industry context and need in each case. Hence, we have had no common questionnaire nor surveys used throughout the cases. We cannot claim that the results from this research are valid for other contexts than described in each of the industry cases.

V. Identifying Industry Needs

Inspired by experience from a similar research collaboration project on knowledge based development we developed an *A3 customer-interest* [55] template for the partners at project start. The purpose of the A3s was to gain a thorough understanding of the current needs for a new methodology within each of the industry partners. We introduced the A3s to the partners in the first half-yearly workshop in the research project. Using the A3 as a guide, we performed informal interviews with company representatives from each of the industry partners. We summed up the following industry needs: *1) early validation*, *2) transfer of (human) insights*, and *3) early concept exploration* to discover "wow" innovations. "Wow" is in this paper defined using the more academic term significant innovation [13], which is the main goal of the research project. Figure 1 visualizes the main industry needs within the context of a system's life cycle [1].

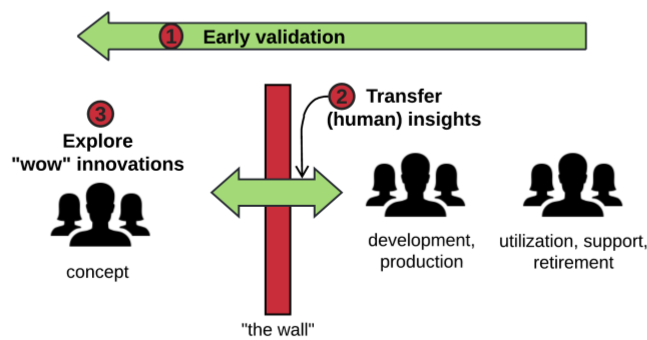

Figure 1. Industry needs in the context of a system's life cycle

Point 1 in Figure 1 shows the industry need to perform early validation of concepts towards a system's operational life cycle (utilization, support, and retirement). This describes the need for better understanding the usage of the system in the concept phase. Point 2 in the figure shows the need to transfer insights gained in the concept phase towards later life cycle phases. The company representatives described this challenge as *"throwing concepts over the wall";* hence, there is a lack of knowledge sharing between concept and development phases. Point 3 in the figure represents the industrial need to create significant innovations through concept exploration. Norway being a high-cost country, the companies need rapid ways of doing this to stay competitive in a global market.

In parallel with the early interviews with company representatives, we performed a literature review on *design thinking* and *systems engineering* as part of early case studies within the industry partners [42]. Thereafter we synthesized the knowledge gained from the literature and interviews, and derived *success criteria* to evaluate the toolbox. For triangulation purposes, we further evaluated the criteria using a survey towards the company representatives. We provided the survey to the eight company representatives in the research project in one of the half-yearly workshops. Prior to the survey, we presented the rationale behind the success criteria to the company representatives. Table 3 shows the profiles of the respondents.

Table 3. Profile of respondents

Role	Company	Relevant work experience (years)
Project manager	A	11
Ux-designer	B	6
System architect	B	4
Department manager SE	B	20
General manager	B	25+
Program manager	C	20+
Technical manager SE	D	13
Chief product developer	D	25

Using Likert scale [56] with the options *very low, low, medium, high,* and *very high,* the respondents answered the two statements:

S1) How important do you think the different properties below are for a new method for the project team in early phase innovation?

S2) How well are the different properties satisfied by the current way of working in early phase innovation in your company?

We analyzed the survey results using a Net Promoter Score (NPS) [57], [58]. We consider the promoters as the ones replying *very high*, while the detractors are the ones replying *medium, low* and *very low*. *High* is neither promoter nor detractor, and hence left out of the NPS score. Table 4 shows the identified success criteria and the NPS results of the survey.

Table 4. Success criteria with NPS results

Success criteria	S1: perceived important for a new method	S2: satisfied by current way of working
Striving to fail early	-3	**-8**
Grasping complexity	**2**	**-7**
Showing business potential	**4**	-4
Sharing knowledge	**1**	-4
Visualizing	**4**	-4
Focus on customer	**4**	0
Enabling creativity	0	-3
Focus on user	**1**	-3
Adaptable to project need	**2**	-4

Table 4 shows the promoted success criteria (NPS > 0) and the most challenging criteria in current work processes (NPS < -5) in bold. For S1, the industry partners were surprisingly not promoting the two criteria; *striving to fail early* and *enabling creativity*. These are factors often highlighted as important for innovation, such as in literature on design thinking [37]–[39]. Reformulating the criterion “striving to fail early” into the more positive “rapid learning” might have provided a more positive NPS score from the industry partners. A negative NPS score for “enabling creativity”, might be related to company culture and history. Based on the solid foundation in literature, we choose to keep these two criteria.

Further, for S2 the companies identified *striving to fail early* and *grasping complexity* to be the most challenging criteria to fulfill in current way of working. The companies also perceived that they currently have enough *focus on customer*.

The last criterion in Table 4; *adaptable to project need*, is at a meta-level with respect to the other criteria, describing the success criterion about the toolbox (irrelevant of its content). The NPS score of -4 indicates that the companies perceive their current way of working as not fit and too rigid for the various needs within a project team. The new methodology needs to be flexible enough to fit the various needs of the systems engineers working in the concept phase.

VI. Exploring a Toolbox

This section describes the industry cases on the methods and tools. We conducted ten cases, applying six methods and tools. Table 5 shows the methods and tools in the toolbox, industry cases, and the theoretical field for positioning the methods and tools.

Table 5. Overview of methods and tools in the toolbox

Methods and tools	Case (company)	Theoretical field
Gigamapping	1 (all)	Systems oriented design
Visual canvas	2 (B), 3 (B)	Design thinking
IKA	4 (B), 5 (A), 6 (D)	Systems architecting
Systemigram	7 (D)	Systems thinking
Illustrative ConOps	8 (D)	Systems architecting
Co-creation sessions	9 (B), 10 (B)	Participatory design

A. Gigamapping

We applied gigamapping in one case covering nine sessions within all the four companies. Gigamapping stems from systems oriented design. It is a session-based method used to explore complex problems through sense sharing [47], using large sheet of papers on walls or tables.

In **Case 1**, an experienced gigamapping facilitator introduced the method to the companies [59]. From there on, members of the research team facilitated the sessions. We applied gigamapping in idea generation, concept exploration, and concept development. The number of participants in the sessions varied from 4-12 participants. Figure 2 shows small teams doing gigamapping on table and wall (in the back).

Figure 2. Small groups doing structured gigamapping

The team in front was exploring a new concept over its lifecycle using structured gigamapping with timeline. Most participants expressed enthusiasm during and straight after applying the technique. Participants of two early sessions using gigamapping were replying to the following Likert scale [56] statement after the session: *"I will try out the techniques we used in this workshop in my future work."* All 22 participants replied agree or strongly agree to this statement, with an NPS [57] of 13. The ship designer cleared off a separate room for gigamapping just after the introduction, determined to further test this way of working.

Main benefits that the participants replied after gigamapping were a better understanding of complex problems and stakeholders. They also reported that gigamapping enabled communication and ensured that all participants were on the same page. Main concerns that the participants replied after gigamapping were whether all necessary participants were present, if the actions would be followed-up, and how to ensure using gigamapping as part of the daily work. Another challenge mentioned by participants was that gigamapping was suited for extrovert people.

B. *Visual canvas*

We applied visual canvas in two cases in company B. Inspired by design thinking, visual canvases are designed to extract human values enabling design of systems that are *desirable, feasible, and viable* [40].

In **Case 2**, Pinto *et al.* [40] implemented two visual canvases in a system development project in the innovation consultancy. The project team used the canvases for stakeholder analysis and use case scenarios. Pinto *et al.* found the tool to increase the project team's focus on human values. The team developed system requirements reflecting the identified human values.

Sjøkvist *et al.* [50] conducted further evaluation in **Case 3**. They implemented visual canvases in an early concept study for a customer in the construction industry. In addition to Pinto's canvases, they implemented visual canvases for stakeholder mapping and stakeholder interviews. The project team used the canvases for documentation and communication towards customer and within the project team. Sjøkvist *et al.* observed that the project team found it challenging to maintain the focus on human values throughout the concept phase. However, they found that visual canvases contributed to a stronger awareness of human values among the systems engineers. The team successfully managed to transfer human values into stakeholder requirements.

C. *IKA*

We applied IKA in three cases in companies A, B, and D. IKA [27] is a tool developed in MS PowerPoint for knowledge sharing in the concept phase in company B. It is documenting knowledge captured by tools such as visual canvases or co-creation [40], [50]. Inspired by design thinking and informal methods in systems architecting, IKA uses visualizations and interactive links to provide a usable and desirable interface for the systems engineers.

In **Case 4**, Jensen *et al.* [27] found IKA to support effective documentation and communication within the project team and to customer at the innovation consultancy. The systems engineers perceived IKA as more desirable than current way of working. Jensen *et al.* also found the tool to be effective in status meetings, as a structured knowledge base for building the problem and solution landscape within the project team.

In **Case 5**, Vanebo and Kjørstad [51] found IKA to be beneficial for creating a mutual understanding of customer needs within the project team. The format and layout of the IKA showed potential for presentations to customers. Vanebo *et al.* also found the IKA as a potential knowledge base for the project team in the concept phase and for knowledge transfer to teams in the following life cycle phases. The concerns reported by the systems engineers were the amount of work required to develop and maintain the IKA. They also reported the need for a document owner and revision control.

Case 6 applied IKA in a project team at the EPCI supplier (company D). Figure 3 shows the IKA front page.

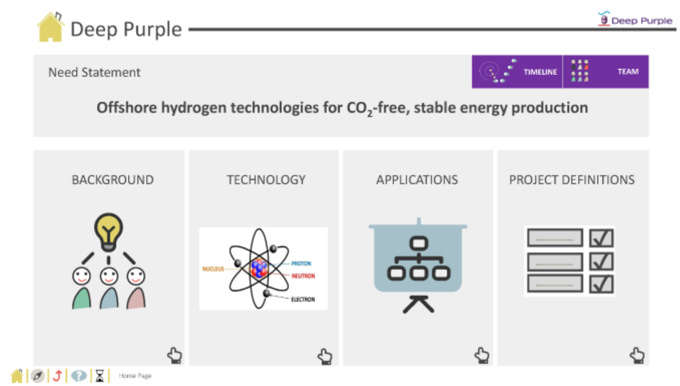

Figure 3. Front page of IKA applied in company D

The team was doing concept design of a renewable energy system to provide off grid, stable, emission-free energy to maritime applications. As three new team members entered the project at that time, the team used IKA as a knowledge base and for knowledge transfer to new team members. The team tested IKA for eight months.

The main benefit observed during development of the IKA, was that to communicate in this format the systems engineers needed to be specific and simplify concepts. The navigation links also gave a rapid knowledge transfer for new team members. The main concerns reported by the team members was that the IKA layout suffered from a lack of quality check and that it required a lot of maintenance. Another comment was that the value of IKA depended on its design. The IKA did not necessarily increase the understanding of customer needs but ensured the transfer of the knowledge gained. We observed that the IKA did not replace any of the other documents in the project. The systems engineers perceived maintaining IKA as added work.

D. *Systemigram*

Systemigram was applied in one case in company D. Systemigram [28] is a systemic visualization for capturing concepts through a systems thinking mindset, and used for communication of strategic intent.

In **Case 7**, Kjørstad, Mansouri, Muller and Kjenner [52] investigated how systemigram could benefit the renewable energy project at the EPCI supplier (company D). At the time of the case, the renewable energy project was still in concept exploration phase with high focus on communicating business case towards internal and external stakeholders. Kjørstad *et al.*

developed a systemigram visualizing the business case with focus on user needs. The systemigram was included in the IKA. Kjørstad *et al.* found the systemigram to provide an effective way of communicating the business case towards external stakeholders, allowing the presenter to highlight the important aspects instead of diving into confusing details. The external stakeholders, not previously exposed to systemigram, found it to be an informative and fascinating way of communication. Developing the systemigram was a time-consuming process; however, the process itself increased the systems engineers' understanding of the system and its context.

E. Illustrative ConOps

Illustrative ConOps was applied in one case in company D. Illustrative ConOps [25] is a visual representation of the sequence of operation of the concept(s), usually captured in an A3 format. Illustrative ConOps can be used for early validation of concepts in communication towards stakeholders.

Case 8 designed an illustrative ConOps of a maintenance operation for the renewable energy system in company D. Inspired by the focus on human values in Case 2 and 3, Aarsheim, Falk and Kjenner [53] developed a semi-structured interview guide to find how the users perceived the maintenance tasks. Combined with the illustrative ConOps, the project team conducted interviews with users holding operational experience from offshore subsea systems. The project team considered this as a feasible option as the company had no access to users of similar systems. Aarsheim *et al.* found the illustrative ConOps to increase the systems engineers understanding of human values. Furthermore, they successfully transferred this knowledge into stakeholder requirements not previously identified by the project team. They also observed that the interviewees reacted with surprise to the focus on human values, clearly expecting a more technical and business focus.

F. Co-creation sessions

We applied co-creation sessions in two cases in company B. Co-creation sessions are carefully planned sessions for concept explorations. The sessions are carried out in collaboration with customers with the intention of early validation. Through facilitation, the participants apply tools and techniques inspired by design thinking, systems architecting and business theory.

Case 9 investigated a co-creation session in three different innovation projects within the innovation consultancy (company B). Kjørstad *et al.* [42] found the main drivers for co-creation sessions to spark creative ideas and explore early phase concepts, enable customer ownership of chosen concepts as well as create a mutual understanding of the user needs. Further, they found the main impacting factor of the effectiveness of the method to be the skill of the facilitator.

In **Case 10**, Guntveit, Kjørstad and Sevaldson [54] did further research on how co-creation sessions contributed to early validation of stakeholder needs. They planned and facilitated three sessions with three different customers. Guntveit *et al.* found that the co-creation contributed to anchor, align, and validate stakeholder needs. However, they also found that the sessions themselves did not necessarily help for eliciting stakeholder needs. The project team needs to identify this insight upfront and include it in the session.

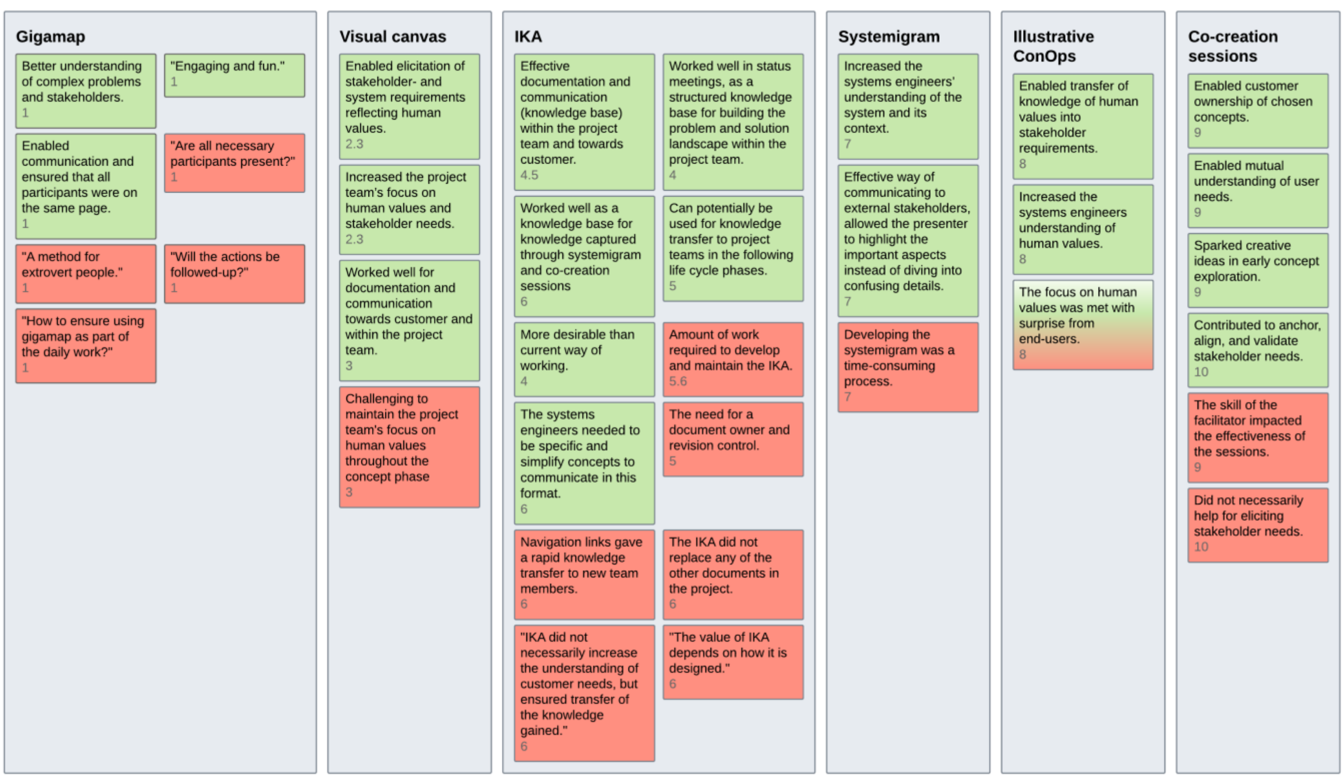

Figure 4. Pros (light green) and cons (dark red) of the methods and tools in the toolbox (including reference to case no.)

VII. Analyzing the Toolbox

Figure 4 presents a summary of the pros and cons applying the toolbox. Table 6 shows how the toolbox addresses the success criteria. Based on the findings in Figure 4, this section analyzes the industry cases on the toolbox and discusses how the methods and tools satisfy the success criteria (highlighted in *italic).*

Table 6. How the toolbox addresses the success criteria

Methods and tools	Success criteria
Gigamapping	Grasping complex problems, sharing knowledge, enables creativity
Visual canvas	Focus on user
IKA	Sharing knowledge
Systemigram	Showing business potential, focus on customer, sharing knowledge
Illustrative ConOps	Striving to fail early, visualizing
Co-creation session	Enabling creativity, striving to fail early, focus on customer, share knowledge
All (the toolbox)	Adaptable to project need

In Case 1, we observed that **gigamapping** works well for *grasping complex* problems and *sharing knowledge* through interactive sessions. It is a visual tool for exploration and in this way, it *enables creativity*. Participants perceived gigamapping as a tool for extrovert people, and a question often popping up afterwards was how to proceed. Facilitators must ensure that introvert participants engage too.

In Case 2 and 3, we found **visual canvases** to increase awareness of human values through *focusing on the user*. The project teams used the canvases to identify needs and transforming them into stakeholder and systems requirements. In Case 8, we observed that direct contact with end-users is not always possible nor even known nor prioritized in the early concept exploration phase.

IKA seems to work well in small-sized companies used to flexible work processes, such as in Case 4 and 5. It is a rapid way of communicating concepts. All cases on IKA found it to work well for *sharing knowledge*. It was acting as a knowledge base for the knowledge captured by the other methods and tools. Case 4 also proposed to use IKA for knowledge transfer towards systems engineers in subsequent life cycle phases.

Systemigram as applied in the renewable energy project in Case 7, is a slow but helpful tool to *show business potential* and *focus on customer*. We also found the systemigram to work well as a communication tool for *sharing knowledge* towards external stakeholders. The case shows that the process of developing the systemigram is as least as important for knowledge sharing as the result itself.

In case 8, we found **illustrative ConOps** to be effective for early validation of user needs, and in this way offers a good approach *to fail early* and to learn rapidly. Designing *visual* representations of operational scenarios forces the systems engineers to *focus on users*. We found that the focus on human values enabled systems engineers to elicit new stakeholder requirements.

Case 9 and 10 found **co-creation sessions** with a planned agenda and carefully chosen tools to work well to engage customers, create trust, *enable creativity*, and explore the problem and solution landscape. Through exploring concepts in collaboration with customers, the session *strives to fail early* and learn fast, as well as *focus on customer* and *share knowledge* through interaction. Case 9 found the outcome of the sessions to be depended on the skill of the facilitator. This sets certain requirements to the facilitation skills of the systems engineers.

We found most of the methods and tools in the toolbox to be flexible and *adaptable to project need*. Visual canvases are not that easily adapted if contact with end-users is not possible. However, this challenge can be mitigated using visual canvases towards feasible options, such as in Case 8. The co-creation sessions as used in Case 9 and 10 are not necessarily adaptable to a project without a customer. For such projects, a modified co-creation session using similar tools and approaches might be beneficial for internal concept exploration. It is also interesting to note that focus on human values and emotions is less expected in some domains than others (as experienced in Case 8). Further, we see that the IKA in Case 4 and 5 (company B and A) seem more promising than in Case 6 (company D). We assume that the size of the company might affect these results, as medium sized companies usually have more flexible ways of working than larger companies with rigid work processes.

VIII. Towards a Methodology

This section outlines the new methodology as the authors envision it at the current point in time. The outline is based on the experiences from exploring the toolbox through the ten industry cases.

To support exploration and validation of early phase concepts, we find that systems engineers may benefit from applying more collaborative and creative ways of working than supported by traditional systems engineering. Collaboration expands the perspectives of the systems engineers and ensure stakeholder and context understanding. Knowledge of multiple perspectives supports a systems thinking mindset to develop a system fit for purpose. Creativity enables exploration of the problem space towards significant innovations. Co-creation sessions focus on both collaboration and creativity by applying techniques for exploring the problem and solution domain. Such sessions require careful planning and strong facilitation skills. Rather than facilitate co-creation sessions in its full, we propose to find inspiration from the techniques applied in the sessions and make use of shorter and more iterative sessions.

To further support systems engineers to explore and early validate concepts towards a system's operational life cycle, we see the need for systems engineers to explore user needs and operational scenarios. Tools such as visual canvas and illustrative ConOps are suitable for this purpose. Making visualizations forces the system engineers to simplify ambiguous concepts. The outcome of the illustrative ConOps and systemigrams is a tangible artifact that eases discussion in the team and with customers. Using a knowledge base, such as IKA, to store this kind of artefact supports the transfer of insights towards later life cycle phases. Based on the findings from the cases applying IKA, we propose to integrate such a knowledge base to a more formal architectural framework, similar to what proposed by Cloutier, Sauser, Bone, and Taylor [30]. A digitized IKA will reduce the need of maintenance and revision management. The knowledge base should still strive to keep an intuitive and desirable format for the systems engineers to make use of it.

We have found knowledge sharing, with the purpose of transferring insights to be multidimensional. Session-based tools, such as gigamapping and co-creation sessions, support sense sharing between people as part of a sense-making process. Sense sharing is important for a team to make sense of complex problems. However, the insights gained during such sessions also need to transfer to people not being part of the process. We see a need to capture and transfer the insights gained from sense sharing into the knowledge base. This requires systems engineers that have this insight, as well as the skill to order and visualize it. The process of making systemigrams supports sense sharing by the people part of the process, and the systemigram itself enables knowledge sharing to people not part of the process. Our findings from the case show that systems engineers may perceive the process of making them as time consuming. The value of systemigram needs to be clear for the systems engineers to apply it in their daily work.

The new methodology needs to be flexible, to support systems engineers holding various skills and ways of working. The methods and tools in the toolbox support the main industry needs in several ways and are complementary. The toolbox is a proposal, other methods and tools with similar purpose may be equally beneficial when combined in the same way. For the new methodology, we propose a balance of concept exploration and early validation of concepts moving towards significant innovation at a rapid speed. The systems engineers need to hold a strong focus on capturing insights in a visual format. Tangible concepts decrease uncertainty and enable rapid learning. In future research, we will elaborate on further realization and evaluation of the new methodology and aim to provide an industry guide.

IX. Conclusion and Future Research

Norwegian high-tech industries face a rapidly changing market need. Staying ahead of competitors and developing significant innovative solutions are essential for business value. We find that systems engineers may benefit from applying more collaborative and creative ways of working than traditional systems engineering offers. This paper explores a toolbox and the outline of a new methodology for such co-creative problem solving. The new methodology should support systems engineers to cope better with the complexity of soft systems in the development of significant innovations. Through ten industry cases within four Norwegian high-tech industries, we have analyzed and discussed a rich toolbox embodied in the new methodology, aiming to answer three research questions.

1) What are the industry needs for a new methodology to innovate in a soft systems context?

Through informal interviews and surveys within the four industry partners, we have identified three main industry needs for a new methodology. Figure 1 captured the main needs as *1) early validation of concepts* towards a system's operational life cycle, *2) transfer of (human) insights* between concept and development phases, and *3) early concept explorations* for significant *"wow"* innovations.

2) How does the toolbox address the industry needs?

We explored a toolbox consisting of six methods and tools to be embodied in the new methodology. *Visual canvas* and *illustrative ConOps* support systems engineers to explore user needs and operational scenarios. Visual canvas, illustrative ConOps, and *systemigram* produce visual artefacts that enable discussions, early validation, and rapid learning. The artefacts can be used for knowledge sharing to ease transfer of insights through an intuitive and desirable knowledge base, such as *IKA*. Session-based methods, such as *co-creation sessions* and *gigamapping*, provide multiple perspectives and transfer insights in the form of sense sharing through concept exploration.

3) What may be the outline of the new methodology?

The methods and tools in the toolbox complement each other in supporting the industry needs. The toolbox is a proposal, other methods and tools with similar purpose may be equally beneficial when combined in the same way. The new methodology needs to provide flexibility to support systems engineers with different skills and ways of working. We propose a proper balance of exploration and validation of concepts, as well as a strong focus on creating tangible artifacts to decrease uncertainty and enable rapid learning. In future research, we will elaborate on the realization and evaluation of the new methodology, aiming to provide an industry guide.

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Article 4

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systems

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Article

Co-Creative Problem Solving to Support Rapid Learning of Systems Knowledge Towards High-Tech Innovations: A Longitudinal Case Study

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Abstract: This article explores co-creative problem solving to support rapid learning of systems knowledge in the concept phase towards innovation. We introduce the term co-creative problem solving to describe the act of collective creation between systems engineers and stakeholders during problem solving. The context of this research is a mature Norwegian industry accustomed to efficiency and risk aversion, challenged by late validation of systems design due to poor utilization of systems knowledge. We have explored co-creation between systems engineers and stakeholders such as project managers, business developers, and subject-matter experts through a longitudinal in-depth industry case in the energy domain. The primary outcome is insights into how co-creative problem solving supports rapid learning of systems knowledge in the industry case. We propose a method building on the findings from the research results to support systems engineers in similar contexts facing similar challenges.

Keywords: creative problem-solving; co-creation; innovation; complex systems; system of systems; systems architecting; systems engineering

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1. Introduction

Co-creation was coined by Prahalad and Ramaswamy in 2004 [1], focusing on the concept of co-creation between enterprises and consumers with the purpose of value creation and innovation [2–5]. The use of co-creation in the marketing domain has grown significantly in the last decade [6] and proliferated to other domains such as design, focusing on collective creativity between designers and stakeholders [7–11]. The value of co-creation in systems engineering is less explored. This article seeks to extend co-creation in systems engineering [12], focusing on co-creation between systems engineers and stakeholders such as project managers, business developers, and subject-matter experts. Inspired by Sanders and Stappers [9], we introduce the term co-creative problem solving to describe the act of collective creativity between systems engineers and stakeholders during problem solving in the concept phase of systems development.

People, organizations, and technical functionality contribute to increasing complexity in today's high-tech systems. Checkland and Wilson described such sociotechnical problems as real-world problems and introduced the Soft Systems Methodology (SSM) to address this [13–17]. Jackson [18] introduced Critical Systems Thinking to combine systems approaches and cope with various forms of complexity. We define systems knowledge as knowledge of the system [19] over its life cycle and this underpins the research in systems theory [20]. Due to the ambiguous and uncertain nature of the concept phase, systems engineers should strive for rapid learning of systems knowledge and early validation of systems design. Collective creativity in problem and solution exploration using co-creative workshops [21,22] and creative problem-solving teams [23,24] has been shown to be suitable for this purpose.

Co-creation and similar human-centric approaches aim to support the creation of significant innovations in collaboration with customers and users [11,25–27]. We distinguish between incremental and significant innovations, the latter meaning solutions beyond the ordinary (The Boderc research project [28], conducted through the Embedded Systems Institute in Eindhoven, the Netherlands, inspired this terminology). Mature organizations often rely on consolidation and incremental innovation to grow, while significant innovations are much harder to create [29,30]. A challenge for mature companies is that their approaches are often more suitable for incremental innovation than significant innovation. The neglect of the importance of collaboration and creativity in systems development is a typical challenge identified among engineers in the energy domain [31]. West [32] claimed that creativity is relatively easy as most engineers are highly creative. However, transforming creative ideas into innovative concepts is more difficult due to "resistance to change and structural and cultural barriers" [32]. In this article, we seek to bridge these barriers and explore how co-creative problem solving may support the creation of significant innovation in a mature Norwegian high-tech company.

The research presented in this article is part of a research collaboration project with four Norwegian high-tech industry partners and two academic partners in systems engineering and systems oriented design, respectively. In our former research, we identified that the industry needs to support rapid learning of systems knowledge through concept exploration, early validation, and knowledge transfer in the concept phase [33]. Furthermore, we explored the use of co-creative methods and tools [21,22,34–38] to support the Norwegian high-tech industry in achieving their needs. We concluded on eight success criteria inspired by systems and design theories for a new way of working.

In this article, we apply the success criteria as a guide to explore and analyze the usefulness of co-creative problem solving in an industrial setting. For two years, we have interacted with a development team at one of the industry partners. The industry partner is a large-size global engineering, procurement, construction, and installation (EPCI) supplier with about four decades of EPCI experience in the energy domain. A company accustomed to a business management system based on typical (hard) systems engineering focusing on efficiency and risk aversion. The company is currently developing an innovative renewable energy system for the ocean space named Deep Purple. The innovation is leading the company's transition toward sustainable energy production systems. Deep Purple is an innovative large-scale, complex system of systems, building on the company's excellence in subsea technology. However, the innovation also requires the company to gain new knowledge as they enter a new domain in the renewable market. They need new ways of working to support rapid learning and early validation. Our research has explored the usefulness of co-creative problem solving and gained insights into applying this way of working in the industrial setting.

This article aims at answering the following research questions:

RQ1: How may co-creative problem solving support the systems engineers in rapid learning and early validation?

RQ2: How may the systems engineers apply co-creative problem solving in an industrial setting?

RQ3: What may be the main challenges for the systems engineers to adopt co-creative problem solving as a new way of working?

The primary outcome is insights into how co-creative problem solving supports rapid learning and early validation in the industry case. We propose a method building on the findings from the research results to support systems engineers in similar contexts facing similar challenges.

This article contributes to the body of knowledge in two ways: (1) adding academic rigor to collaborative and creative ways of working in systems engineering, and (2) proposing an industrial-relevant method for systems engineers to apply co-creative problem solving. We apply the notion of rigor and relevance as described by Ivarsson & Gorschek [39].

We structure the article as follows. Firstly, Section 2 provides literature on systems and design practices that have inspired this research. Section 3 introduces the method that evolved in this research, and Section 4 describes the research design. The first stage of that research produces insight into how co-creative problem solving may support systems engineers in the concept phase towards high-tech innovations, aiming to add to the academic rigor (Section 5). The second stage of that research realizes and applies a method for co-creative problem solving in the industry case, aiming to contribute to the industrial relevance (Section 6). Section 7 discusses our findings before concluding in Section 8.

2. Literature Review

This section reviews the literature on systems and design practices that have inspired this research. We also include literature on creativity practices in engineering and general theory on creativity.

Co-creation stems from the enterprise and marketing domain, describing the co-creation between consumers and enterprises as part of the value creation process [1]. In participatory design, Sanders and Stappers [9] described co-creation as collective creativity in any form. They further narrowed this term into co-design and described this as "the creativity of designers and people not trained in design working together in the design development process", with non-designers typically being users or customers [40]. They emphasized the need to view users and customers as partners rather than subjects in the front end of product development. Contemporary design thinking, as practiced by the Innovation Design Engineering Organization (IDEO, Cambridge, MA, USA), the Stanford Design School (Stanford, CA, USA), and the International Business Machines Cooperation (IBM, Armonk, NY, USA), is by many seen as the recipe for innovations [10]. Design thinking practices co-creation using techniques such as rapid prototyping [41]. Design thinking focuses on empathizing with users to create innovative products or services, providing a more extraordinary user experience. IDEO advocated this mindset to create innovative new products and services and transform creative people and organizations [25]. Jones [7] discussed various types of co-creation and identified possibilities for improving design co-creation methods. He highlighted the importance of continuity and investment in this way of working to provide insight into complex problems. Jones called for a systemic design framework to enable practitioners to select and modify the various co-creation methods.

Various literature within systems engineering described the need for collective and creative approaches to creating new products and systems. Pugh [42,43] highlighted the importance of group work and creativity in concept generation and evaluation (the Pugh matrix) as early as the 1980s. Sage & Armstrong [44] proposed collaborative and creative methods for systems synthesis, such as brainstorming [45] and the morphological box approach [46]. Lippert and Cloutier [47] described an extended use of TRIZ [48] to support systems engineers in creating innovations within digital systems engineering. White [49] proposed a practical methodology for complex adaptive systems engineering (CASE) to improve traditional systems engineering in sociotechnical systems engineering. His methodology covered organizational and team aspects, such as the need for brainstorming approaches and user experimentation. The methodology aimed to be an iterative and adaptive way of working for the team to operate on the "edge of chaos" effectively [49].

Looking towards systems architecting, Maier and Rechtin [50] described a great systems architect as being as skilled as an engineer and as creative as an artist. Sillito [51] emphasized the need for an analytic, inventive, and creative process in systems architecting to thoroughly understand the problem and solution domain and create suitable architectures. He distinguished between architecting and architectural modeling, both activities interacting and creating a system fit for purpose. The main objective of the systems architect is to understand how the system behaves and communicate this to others effectively [51]. Muller [52] described facilitating workshops as one of the tools of the systems architect. Workshops enable crossfertilizing and sharing systems insight such as in product specification, design, or business strategy. To conduct effective workshops, Muller proposed timeboxing and multi-views in iteration [53]. Multi-views use a CAFCR [54] framework to view the system from the customer, application, functional, conceptual, and realization perspective iteratively as the concept matures. Timeboxing is to set an appropriate timebox to achieve this within the duration of the workshop.

McFadzean [55,56] supports the importance of multiple perspectives in the engineering of innovative products and systems. She called for a more vigorous use of creativity techniques in engineering and proposed a framework for creative problem-solving teams. The framework enables teams to select appropriate techniques based on their level of experience and need. McFadzean [23,24] further elaborated on the role of a neutral facilitator in such teams. The facilitator needs to address soft issues within the team to establish trust and deal with conflicts. She also described the effectiveness of such teams to depend on their experiences in using creative problem-solving techniques. According to McFadzean, some people may find creative problem-solving techniques uncomfortable. This discomfort can reduce the effectiveness of such techniques. In the worst case, people may not participate at all.

Using groups to stimulate creativity is also supported by Paulus and Nijstad [57]. They found ideas produced by a group more innovative in a productive group setting, considering factors such as trust, attitude, and the number of participants. They proposed the usage of a facilitator and a leader to cope with unproductive team dynamics. The group should be diverse enough to provide knowledge on the subject but not too diverse as this may cause misunderstandings and conflicts. A diverse group enables a change of perspective and stimulates activation of long-term memory, resulting in more innovative ideas. Paulus et al. also found positive effects of combining individual ideation with group ideation to avoid participants biased by each other's opinions and ideas.

Dorst and Cross [58] and Dorst [59] described the importance of coevolving on the problem and solution space by going back and forth on problem and solution exploration to support creative designs. De Bono [60] emphasized the importance of exploring the problem landscape thoroughly to gain insight instead of jumping to a solution. Furthermore, De Bono [60] described lateral thinking as a way of thinking to explore the problem space and stimulate creativity. Without a thorough understanding of the problem and solution spaces, engineers and designers are likely to jump to solutions and develop systems not fit for purpose. Bonnema, Veenvliet, and Broenink [61] (p. 9) identified solution focus as a challenge among engineers in development teams and claimed that "many engineers think in solutions". Daly, Yilmaz, Christian, et al. [62] found that the generation of multiple concepts was crucial in creating innovations to avoid such fixation. Furthermore, Murray, Studer, Daly, et al. [63] emphasized the importance of problem exploration perspectives to create innovative designs.

3. A Method for Co-Creative Problem Solving

This section introduces the method that we realized and applied in the industry case. Figure 1 illustrates the method, composed of a three-stage process and a timeline. The three-stage process evolved as we explored sessions in the industry case and bears similarities to best practices for conducting effective meetings such as [64]. Systems and design practices focusing on collective creativity in problem and solution exploration (Section 2) inspired the timeline.

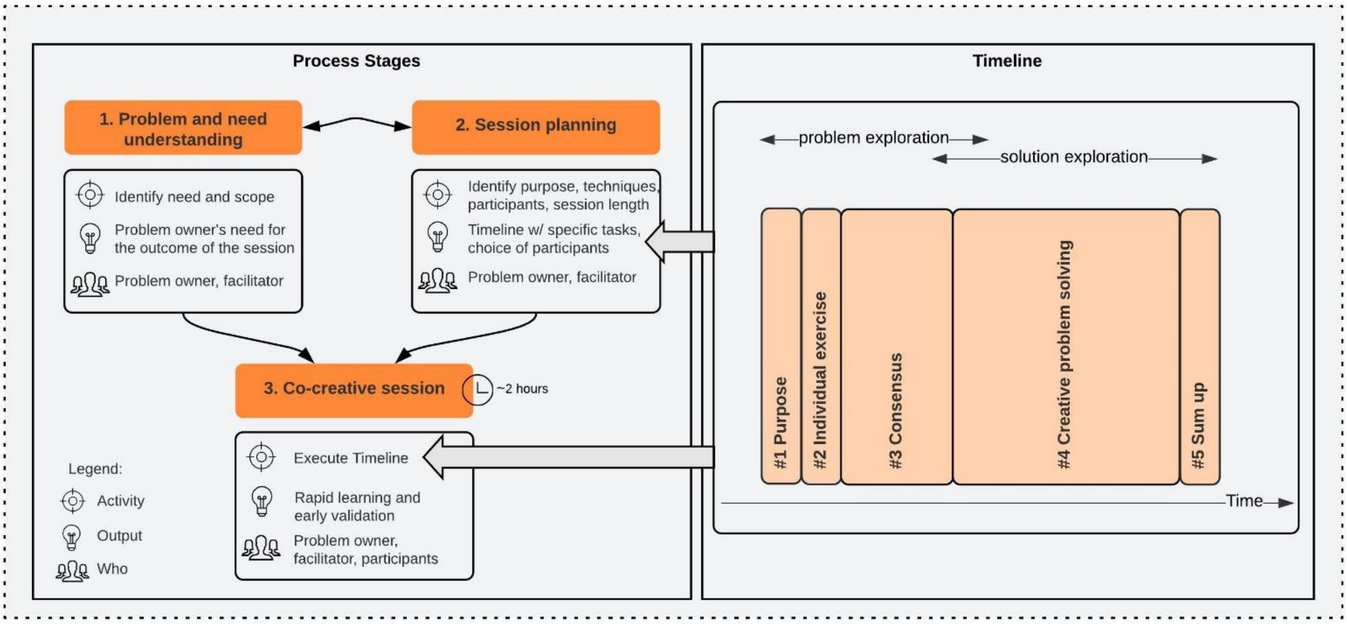

Figure 1. A method for co-creative problem solving.

The method distinguishes from an expert-led co-creation workshop in primarily two ways:

- it supports the use of inexperienced facilitators to conduct the sessions, as the systems engineers in the industry case lacked such experience;
- it emphasizes the use of brief sessions to fit within a busy workday for the participants in the industry case.

In Stage 1, the problem owner and the facilitator gain an understanding of the problem. They identify the need of the session and decide on the scope. The primary outcome of this stage is a mutual understanding of the problem owner's need for the session's outcome. In Stage 2, the problem owner and the facilitator identify the purpose of the session and choose relevant participants. They plan the timeline and select specific techniques fitting the purpose and the participants. The primary outcome of this stage is the timeline, including specific tasks and the choice of participants. In Stage 3, the problem owner and the facilitator conduct the session in collaboration. The facilitator facilitates the participants through the tasks in the timeline while the problem owner leads the session. The primary outcome of the session is rapid learning and early validation.

The timeline in Figure 1 consists of five main tasks for a structured problem and solution exploration. It is the combination and order of the tasks that are important in its co-creative problem-solving capabilities. The timeline aims to create a collective understanding and shared ownership for the participants regarding both the problem and solution space. Furthermore, the timeline combines individual and group exercises to prevent blocking and to enable the participants to build on each other's perspectives. Task #1 Purpose informs the purpose of the session to get the participant to aim towards the problem identified in Stage 1. In Task #2 Individual exercise, each participant reflects upon the problem and provides their views using simple artifacts, such as sticky notes.

Furthermore, in Task #3 Consensus, the facilitator facilitates discussion of these views in plenum and adapts the session's problem description accordingly to share ownership. In Task #4, Creative problem solving, the facilitator facilitates the participants in a creative problem-solving technique to support the participants in challenging systems boundaries and exploring multiple perspectives. Finally, in Task #5 Sum-up, the facilitator sums up the session and connects to the problem description. This task verifies that the solution exploration fits the session's problem and stimulates reflection among the participants.

4. Research Approach

Action research forms the basis of this research and allows the researcher to acquire knowledge of real-world problems and improve [65]. In this research, we conducted a longitudinal study of about two years within the development team in the concept phase of developing the Deep Purple system at the industry partner. Deep Purple is a complex system of systems leading the company's transition toward sustainable energy production systems. Thus, we selected the participants in the development team as we consider Deep Purple as a representative industry case to explore co-creative problem solving. The main author actively engaged with the team in the concept phase of developing the Deep Purple system. The participants represent both genders and hold formal education in engineering and systems engineering disciplines. Table 1 shows the profile of the team members, including years of relevant work experience, which reflect the participants' age.

Table 1. Profile of the team members in the development team. [1]

Role	Years of (Relevant) Work Experience
Project Manager	20
Business Developer	22
Study Lead	25
Expert Systems Engineer	40
Engineering Manager	14
Process Engineer	19
Technical Lead	14
Project Engineer	6

[1] Additional subject-matter experts were participating in Sessions 3, 4, 5, 9, and 11.

Figure 2 illustrates the research design. The first rectangle shows our previous work [33], where we identified the industry needs and the success criteria (Table 2). The two following rectangles of Figure 2 show the two stages of research presented in this article. In Stage 1, we explored and analyzed nine sessions to gain insight into how co-creative approaches supported the systems engineers in the industry case to achieve the success criteria. In Stage 2, we used the insights gained from Stage 1 to synthesize and apply a method to support the systems engineers in co-creative problem solving.

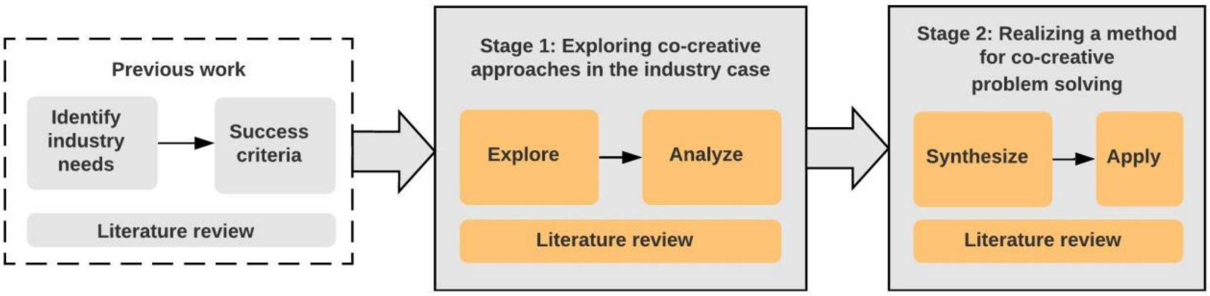

Figure 2. Research design.

4.1. Methodology in Stage 1—Exploring Co-Creative Approaches in the Industry Case

We planned sessions guided by the formerly identified success criteria (Table 2) combined with inspiration from design and systems practices, including creativity practices in engineering and general theory on creativity. We adapted to the team's daily challenges during concept development and planned for sessions when a team member had a specific problem and needed to gather stakeholders and discuss. The researchers and team members facilitated the sessions, neither holding any previous facilitation skills. We did not aim for one session to fulfill all criteria; instead, we used the criteria to gain insight into how co-creative approaches could support the team to achieve the criteria.

Table 2. Success criteria (adapted from [33]).

SC	Success Criteria	Academic Field [1]
1	Striving to fail early	Participatory design, design thinking
2	Grasping complexity	Systems oriented design, systems architecting
3	Showing business potential	Systems engineering, design thinking
4	Sharing knowledge	Design thinking, participatory design
5	Visualizing	Systems thinking, participatory design
6	Focusing on customer	Systems oriented design
7	Enabling creativity	Systems thinking, participatory design
8	Focusing on user	Participatory design, systems oriented design, design thinking

[1] The positioning reflects the authors' opinions of the main academic field(s) to support the given criterion based on the findings from the former research results.

During the sessions in Stage 1, we conducted participant observations and passive observations. After the sessions, we conducted informal interviews, focus groups, and questionnaires. The questionnaire included a set of statements derived from the success criteria using a five-point Likert scale [66]. The scale ranged from strongly disagree, disagree, neutral, agree, to strongly agree. The questionnaire also included open-ended questions for participants to report on benefits and concerns. The Likert scale responses were analyzed using a Net Promoter Score (NPS) [67,68]. Promoters reply strongly agree, while the detractors reply neutral, disagree, or strongly disagree. Agree is neither promoter nor detractor and hence left out of the NPS score. Appendix A provides the questionnaire results, including NPS.

Table 3 provides an overview of the sessions conducted in Stage 1, the context of the sessions, the number of participants and respondents to the questionnaire, and corresponding methods for data collection. We collected data during the planning of the sessions, during the sessions, and from the participants after the sessions using questionnaires and focus groups.

Table 3. Overview of the sessions conducted in the development team in Stage 1.

Session	Context	Participants (Respondents)	Methods for Data Collection
S1	Hazard identification analysis	6 (3)	Participant observation, questionnaire
S2	Technology qualification review	6 (5)	Participant observation, questionnaire
S3	Idea generation for research proposal	6 (4/1)	Participant observation, questionnaire
S4	Early concept exploration of the control design	6 (4)	Participant observation, questionnaire, informal interview
S5	Early phase review of the subsea storage design	6 (3)	Participant observation, questionnaire
S6	Idea generation early-phase pilot project	4	Participant observation, focus group
S7	Lessons learned from a pilot project	5	Participant observation, focus group
S8	Early phase review of water treatment design	5	Participant observation, focus group
S9	Review of subsea storage design including installation	7	Participant observation, focus group

To analyze the sessions, we found inspiration in the framework proposed by Midgley, Cavana, Brocklesby, et al. [69] for evaluating systemic problem structuring methods. The framework focuses on "the use of a particular *method* (or set of methods) in a *context* for particular *purposes*, giving rise to *outcomes*". We view the *method* as the proposed method (Section 3), the *context* as the industry case, the *purposes* as the sessions, and the *outcome* as the goal to support rapid learning of systems knowledge guided by the success criteria (Table 2). While analyzing the sessions in the industry case, we found it beneficial to differentiate between the session's applicability and usability to distinguish between factors impacted by the industry case (the context) and the success criteria (the outcome). Applicability describes how well the session was conducted in the industry case, including planning and structure, while usability describes the session's ability to achieve the formerly identified success criteria.

We categorized the notes into applicability and usability and used the success criteria to code [70] the notes on usability. An example of an interview-note made in S3 and coded with SC3 is "Good suggestions which put the technical solutions into a wider perspective. This will help us to introduce our ideas and solutions to the stakeholders". Assigning the code SC3 "showing business potential" to this note describes the session's ability to view the concept from a business perspective.

Three main capabilities indicating support for rapid learning of systems knowledge in the sessions emerged from analyzing the coded notes on usability. From analyzing the notes on applicability, we identified three impacting factors for applying useful sessions. We made a qualitative assessment of the coded notes for each session and scored each capability in each session using a five-point scale from 1 (very low) to 5 (very high). Sessions providing very low support for the capability scored 1, while sessions providing very high support for the capability scored 5.

4.2. Methodology in Stage 2–Realizing and Applying a Method for Co-Creative Problem Solving

We integrated the findings from Stage 1 into a method to support co-creative problem solving in the industry case. We passively observed the development team for an initial evaluation while applying the method in two sessions, Session A and B. After the sessions, we conducted informal interviews with the facilitator and the problem owner. Table 4 provides details on the application of the method in the two sessions.

Table 4. Application of the method in the industry case.

Session	Context	Participants	Methods for Data Collection
S-A	Prepare high-level visualization of a pilot project for external communication	5	Observation, informal interviews
S-B	Early review of subsea storage architectures	6	Observation, informal interviews

4.3. Validity of Data

This research primarily builds on qualitative and participative research methods. While this approach is valuable to gain an in-depth understanding of industry challenges in their relevant context [65,68,71–73], there is a risk of researcher bias and challenges in the generalization of the research results.

To ensure the trustworthiness of our findings and reduce the risk of researcher bias, we used Maxwell's eight-point checklist for qualitative research [74]. We actively engaged with the systems engineers in the industry case through a longitudinal study to gain an in-depth understanding of their challenges and potential solutions. We conducted nine co-creative sessions with systems engineers and stakeholders to ensure rich data collection from multiple contexts. Furthermore, we triangulated data collection using various methods to analyze the results from multiple perspectives.

5. Results from Stage 1—Exploring Co-Creative Sessions in the Industry Case

This section describes the main results from exploring and analyzing nine sessions in the industry case using the research methodology presented in Section 4.1.

5.1. Conducting Co-Creative Sessions

Table 5 provides an overview of the techniques and artifacts explored in the sessions.

In Sessions 2 to 8, we applied brainstorming [45], brainwriting [75], and Gigamapping [76] for ideation. In addition, we used other techniques to stimulate creativity, such as coevolving on problem and solutions spaces [58,77], combining individual and group exercises [57], and challenging operational scenarios of concepts through adding or removing constraints [78]. We also explored CAFCR [54], focusing on connecting desired systems qualities to the systems realization and identifying gaps and trade-offs. We explored the use of a playful warm-up exercise inspired by design thinking in Session 5. Furthermore, we used large paper plots, visualizations, markers, sticky notes, flip overs, and a whiteboard.

Table 5. Techniques and artifacts explored in the co-creative sessions.

Session	Techniques	Artifacts	PlanningDuration	Session Duration
S1	Hazard identification analysis (HAZID)	System drawing on A3 printout, guide words on A4 printout, projector, scribe	1 day	1 day
S2	Technology Readiness Levels (TRL), guide questions, technology qualification procedure	Guide questions on A4 printout, review procedure on A4 printout, sticky notes, flip overs, large paper plot, markers	Several days	11 h
S3	Timeboxing, free-format Gigamapping with Z-analysis	Large paper plot on table, flip-overs, markers, need statement on A4 on the wall	30 min	45 min
S4	Free-format Gigamapping including ZIP-analysis	Large paper plot on table, flip-overs, markers	1.5 h	1 h
S5	Timeboxing, warm-up exercise, CAFCR light, individual and group ideation, add concept constraints	Superhero exercise A4 printout, flip-overs, whiteboard, markers, sticky notes, large paper plot on table, system drawing on A3 printouts on the wall	2.5 h	1.5 h
S6	Brainwriting 6-3-5, adjusted to 5-2-4.	Projector showing visualization of a pilot project, brainwriting form on A4 printouts	15 min	1 h
S7	Timeboxing, individual and group ideation	Flip-overs, markers, sticky notes	15 min	1.5 h
S8	Timeboxing, Pugh matrix, individual ideation	Projector showing Pugh matrix, sticky notes	5 min	1 h
S9 [1]	Timeboxing, CAFCR light, individual and group ideation, Pugh matrix	Introducing concepts on a projector, system drawings on printouts on the wall, sticky notes, large paper plot, markers	2 h	2 h

[1] In S9, we could not conduct the session according to plan and did not explore any co-creative techniques. We include the findings from this session as they provide valuable insight into impacting factors for the method's applicability.

Table 6 shows an overview of the number of qualitative field notes from the sessions, including data from observations, interviews, questionnaires, and reflections. The observation notes include field notes made during the session. The interview notes include the notes made during informal interviews, focus groups, and open-ended questions in the questionnaire after the sessions. Furthermore, the questionnaire notes include the most significant promoters and detractors of the statements in the questionnaire (Appendix A). Finally, the reflective notes include reflections made by the researchers after the sessions. The two last rows show the number of notes on the applicability and usability of the sessions, respectively. Applicability describes how well the session was conducted, including planning and structure, while usability describes the session's ability to achieve the formerly identified success criteria (Table 2).

5.2. Analysing the Sessions' Applicability

We identified three main impacting factors for applying useful sessions from analyzing the notes on applicability. These are the understanding of the upfront problem and need, session length, and session structure. The subsequent sections elaborate on these factors.

5.2.1. Understanding of the Upfront Problem and Need

Throughout the sessions, we identified the importance of two roles: the facilitator and the problem owner. The problem owner is the person responsible for the progress of the problem and has an incentive to take on this role. In Session 1, the facilitator took time to discuss with problem owners upfront and carried out a session that satisfied the problem owners' expectations. In Sessions 2 and 4, the problem owner was also acting as facilitator. While this worked well in Session 4, we observed Session 2 suffering from a schedule overrun. A neutral facilitator applying appropriate timeboxes could have prevented this overrun, both during planning and execution.

Table 6. The number of qualitative notes from Sessions 1 to 9.

Type of Note	S1	S2	S3	S4	S5	S6	S7	S8	S9
Observation	7	6	5	1	8	8	8	3	5
Interview	15	20	16	15	14	7	7	1	6
Questionnaire [1]	1	6	1	5	1	-	-	-	-
Reflection	3	3	2	4	8	2	4	8	5
Total	**26**	**35**	**24**	**25**	**31**	**17**	**19**	**11**	**16**
Notes on applicability of Total	20	17	10	10	22	9	8	8	11
Notes on usability of Total	6	18	14	15	9	8	11	3	5

[1] From S6 to S9, we collected data from focus groups and informal interviews.

In Session 4, we posed the following questions to the problem owner and facilitator during planning:

Q1. What does the problem owner want to get out of the session (purpose)?
Q2. Who should participate (background and knowledge)?
Q3. What is the appropriate duration of the session?

The questions were based on findings from Sessions 1 to 3 and inspiration from best practices for effective meetings, such as [64]. Q1 immediately arose when we planned for Session 3. When the problem owner and facilitator aligned on the problem and need, Q2 followed when selecting techniques. From Sessions 5 to 7, we divided the roles of the problem owner and the facilitator more clearly and used the questions (Q1–3) during planning. These sessions provided a useful outcome to the problem owners.

In Session 8, the facilitator and the problem owner used little time to discuss the problem upfront. During the session, it became clear that the planned exercises did not match the need of the problem owner. This session did not play according to the planned agenda, and the outcome was poor.

5.2.2. Session Length

We found that the session length depended on session purpose and commitment from the participants. We found the participants perceived longer sessions as a waste of time in a busy workday. In the sessions with subject-matter experts from other parts of the organization, we observed reluctance to attend more extended sessions due to practical reasons such as lack of cost accounts.

In Session 4, we planned for only one hour, as all participants were subject-matter experts from other parts of the organization. The problem owner was satisfied with the outcome. However, some of the participants reported concerns about too little time. In Session 9, we planned for a full day as the scope of the session was quite large. Likewise, in this session, two participants were subject-matter experts from other parts of the organization. At the last minute, the subject-matter experts canceled the session and replaced it with a two-hour skype meeting. The subject-matter experts were not dedicated to support the innovation and lacked a cost account to attend a full-day session. Sessions 3 to 7 were around 2 h, and we found these sessions to provide a useful outcome within an acceptable timeframe.

5.2.3. Session Structure

In Session 1, the participants showed little responsibility to keep to the scheduled time. The facilitator often cut off discussions between the participants to keep to the scheduled time. There was minimum use of techniques to engage the participants during the discussions. After lunch, the participants were tired and started to wear out. The session could not go through the planned agenda within the scheduled time slot, even though it had a 1-day duration. Session 2 suffered from a schedule overrun. In this session, the participants were engaged using artifacts such as sticky notes, guide questions, and visualizations. The problem owner planned for a session length of about three hours. However, it ended up as three subsessions with a total length of 11 h.

For Sessions 3 to 9, we aimed to activate the participants and conduct structured sessions using engaging techniques and artifacts and shorter lengths. We conducted sessions according to the following structure:

- The problem owner introduces the problem or possibility, good to put visuals or statements up on the wall (in Session 3, this was a specific sentence in a research application form, in Session 5, these were system qualities of the subsea storage concept).
- The participants use sticky notes in an individual exercise to reflect upon the problem.
- Each of the participants present their sticky notes and puts them up on the wall for discussion.
- Creative problem-solving technique, choose the appropriate technique for purpose and participants.
- Sum up by discussing main findings, if relevant make an action list.

We chose timeboxes (Timeboxes set an appropriate length of a task that enables the participants to produce about 80% complete. The reasoning behind this is that 80% is often achievable quickly, while the last 20% is considerably more challenging to achieve and not worth the effort in sessions [53]) fitting to the minimum time achievable for each activity, considering the appropriate session length. The core of the session, being techniques for creative problem solving, required a significant amount of the time. In Session 5, we planned for 60 min for this; the facilitator chose to stop after 45 min due to saturation. In Session 7, we used around 30 min. From Session 3 onward, we found this way of planning agendas to be effective. The feedback and the observations show that the participants appreciated using timeboxes to push them through the activities.

5.3. Analysing the Sessions' Usability

To analyze the notes on usability, we coded the notes according to the success criteria in Table 2. Table 7 shows the number of coded notes in Sessions 1 to 9 for each success criterion. Three main capabilities indicating support for rapid learning of systems knowledge emerged from analyzing the coded notes. The capabilities are problem and solution exploration, collective creation, and creative thinking. To gain further insight into how the sessions supported these capabilities, we scored the usefulness of each session using a five-point scale. Sessions providing very low support for the capability scored 1, while sessions providing very high support for the capability scored 5. Figure 3 provides the scoring results. The subsequent sections elaborate on these scorings.

Table 7. The number of coded notes for each success criterion.

SC	Success Criteria	S1	S2	S3	S4	S5	S6	S7	S8	S9
1	Striving to fail early	1	4	3	3	-	-	-	2	1
2	Grasping complexity	-	4	-	2	-	1	-	-	-
3	Showing business potential	1	1	2	3	-	1	-	-	-
4	Sharing knowledge	2	7	2	7	3	1	10	1	-
5	Visualizing	1	1	1	-	2	-	-	-	1
6	Focusing on customer	-	-	2	-	1	-	-	-	-
7	Enabling creativity	-	-	3	-	3	5	1	-	2
8	Focusing on user	1	1	1	1	-	-	-	-	2

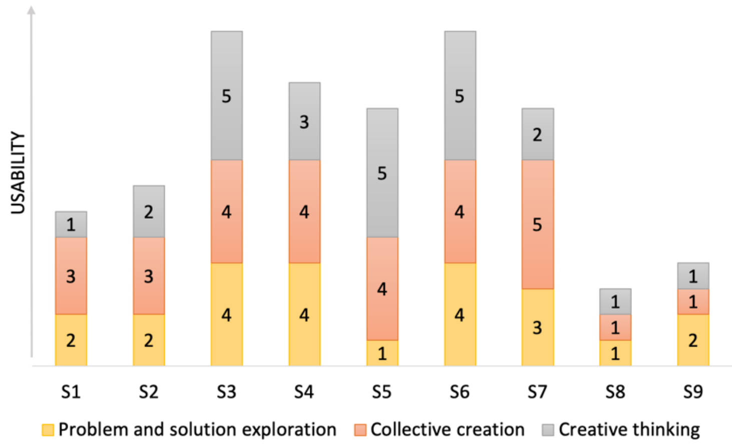

Figure 3. Scoring how the sessions achieve the main capabilities.

5.3.1. Problem and Solution Exploration

We define problem and solution exploration as exploring both the problem and the solution space in the session, considering enabling technology, business case, customer needs, and user needs. In Sessions 1 and 2, we observed the participants primarily focusing on solution exploration and less on problem exploration. In Sessions 3 to 9, we planned for a structured agenda and found this supported the participants in reflecting on and discussing both the problem and solution exploration. Sessions 3, 4, and 6 scored high on problem and solution exploration, while Session 7 scored medium. In these sessions, we observed the problem owner strive to select participants holding the relevant knowledge.

In Session 4, the context of the session was to explore enabling technology for a specific concept that could impact the company's strategy for future applications. We observed the problem owner selecting subject-matter experts holding the knowledge of the enabling technology to validate the current concept early and explore options. In Session 6, we observed the problem owner include business developers to explore possibilities for an early phase pilot project. Further, in Session 5, we observed the problem owner gain awareness of the lack of operational knowledge. As a result, the problem owner included the subject-matter experts holding this knowledge in Session 9.

5.3.2. Collective Creation

We define collective creation as exploring or maturing an idea or concept in the session with a high degree of uncertainty and complexity. Typically, this requires knowledge sharing and striving for early failures. In Sessions 1 and 2, we observed techniques supporting analytical thinking and less exploration. In Session 2, several participants found it challenging to discuss the concept, reporting reasons such as high uncertainty and lack of knowledge. From Sessions 3 to 9, we planned sessions to support the participants in collective creation using techniques to cope with complexity, such as Gigamapping, CAFCR, and ideation.

Sessions 3 to 7 scored high and very high on achieving collective creation. In these sessions, we found the participants appreciated the possibility of sharing their knowledge and perspectives on early phase concepts using techniques such as free-format Gigamapping. In Session 3, the participants reported "rapid identification of possibilities", indicating that the session supported the team in early failures. However, we also reflected after Session 4 that "failing early or perhaps being comfortable admitting that we try to fail is difficult to achieve", indicating that failure is considered harmful in this industry, which focuses on high quality and risk reduction.

We found most participants appreciated the use of creative exercises in the sessions and that participants more experienced using such techniques also appeared to be more confident using them. This confidence became clear in Session 3, where the participants engaged in Gigamapping without further instructions from the facilitator. However, we also observed participants reluctant to engage in creative exercises.

5.3.3. Creative Thinking

We define creative thinking as exploring multiple perspectives and challenging perceived boundaries during problem and solution exploration. In Session 1, we observed a lack of techniques to stimulate creative thinking, such as visualization, engaging techniques, and timeboxes. From Sessions 2 to 9, we made use of techniques and visualizations to support creative thinking.

Sessions 3, 5, and 6 scored high or very high on creative thinking. In these sessions, we found the participants to appreciate the creative artifacts reporting "visual", "creative", "brainstorming", and "sticky notes" as benefits. In Session 6, we found the use of brainwriting combined with group discussion especially beneficial. This combination enabled the participants to think for themselves before discussing their views. Session 6 resulted in 52 ideas in one hour. The participants claimed that the ideas held a higher level of innovation than assumed from a "normal" meeting in the debrief.

Session 9 planned to include creative exercises; however, the subject-matter experts replaced this session with a two-hour "normal" meeting. The problem owner stated in the debrief of the meeting: "This was no creative session; the creativity had happened before the meeting". Furthermore, the problem owner stated that he/she missed the possibility to interact with the subject-matter experts in creative exercises to gain a deeper systems insight.

6. Results from Stage 2—Realizing and Applying a Method in the Industry Case

This section describes the main results from realizing and applying a method in the industry case using the research methodology presented in Section 4.2. We integrated the capabilities and impacting factors identified in Stage 1 into a method. Furthermore, we applied the method in two sessions (Sessions A and B) in the industry case for an initial evaluation. In Sessions A and B, we passively observed the systems engineers applying the proposed method. After the sessions, we conducted informal interviews with the facilitator and the problem owner.

In both sessions, we found the two first stages of the method, understanding of the problem and need and session planning, supported the problem owner to reflect and discuss the problem before conducting the session. Further, splitting the roles of the problem owner and the facilitator forced the problem owner to discuss and reflect on the problem in collaboration with the facilitator before conducting the session. The problem owner enjoyed the possibility to reflect and discuss the problem before the session. The facilitator enjoyed being involved and gaining ownership of the problem.

In Session A, both the problem owner and facilitator found the method provided valuable structure to the session. The structure pressured the participants to share perspectives and explore problems and solutions in a brief time. The timeboxing avoided the participants getting lost in detailed discussions. However, we observed during planning that they failed to plan for an individual exercise and did not include this in the session. In Session B, we observed that the problem owner and the facilitator had difficulties planning for a creative problem-solving technique fitting to the context of the session. They ended up planning to conduct a creative technique on the go. The session was highly talkative, the problem was unclear, and the facilitator could not conduct a creative technique on the fly. We found that both the facilitator and the problem owner appreciated the method during the debrief. However, both missed using a creative problem-solving technique and would plan to use one next time. The facilitator stated that he/she found it challenging to apply a creative exercise as the purpose of the session was unclear. As the facilitator said during the debriefing of Session B, "without creativity techniques, it will only be a lot of talks".

7. Discussion

This section answers the research questions and compares and contrasts the results with existing work in the body of knowledge. The end of this section provides contributions to theory and implications for practice.

RQ1: How may co-creative problem solving support the systems engineers in rapid learning and early validation? Guided by eight success criteria, we planned and conducted nine sessions in the industry case to gain insight into how to realize a method for co-creative problem solving. We identified three main capabilities for a new method: problem and solution exploration, collective creation, and creative thinking. We scored the sessions to gain further insights into how the sessions supported the capabilities and argue that the identified capabilities may support the systems engineers in rapid learning and early validation towards high-tech innovations. Figure 4 illustrates the primary connections between the success criteria on the left and the capabilities on the right. The solid lines illustrate a strong connection between the success criteria and the capabilities, while the dotted lines illustrate a weaker connection.

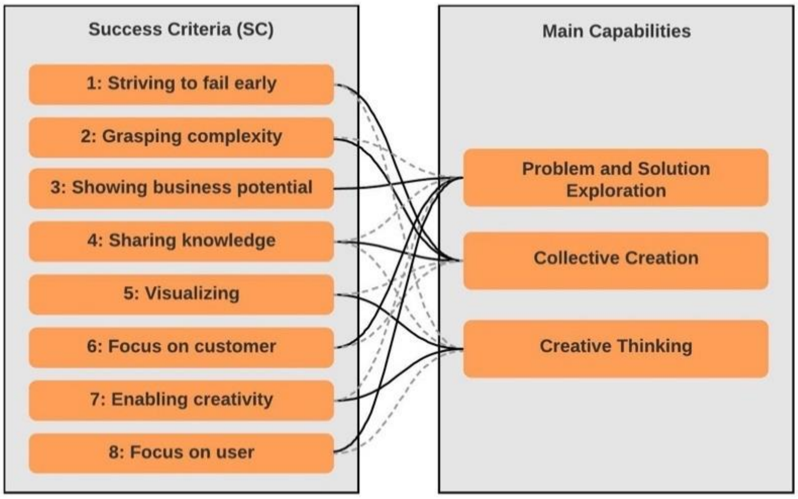

Figure 4. Mapping success criteria to the identified capabilities of a new method.

The importance of a proper problem and solution exploration towards innovation is well supported in literature [55,56,58,60,62,63,77]. Bonnema, Veenvliet, and Broenink [61] (p. 9) identified solution focus as a challenge among engineers in development teams and claimed that "many engineers think in solutions". We identified a timeline to support a structured problem and solution exploration and thus prevent such fixation. The timeline supports a proper problem exploration in the first half and solution exploration in the latter. Furthermore, we found it important that the participants held the required knowledge to conduct problem and solution exploration. Such knowledge typically includes insight into customer needs by *focusing on the customer*, systems operational context by *focusing on the user*, and enabling technology and business case by *showing business potential*.

Co-creation and co-design focus on collective creativity in value creation [1] and design development [9]. Systems-centric approaches such as systems architecting and systems engineering emphasize collaboration, creativity, multiple perspectives in concept generation [42,43], and systems development [44,50,51,54]. To support collective creation, we aimed for *knowledge sharing* of early phase concepts and strived for *early failure* by sharing multiple perspectives using techniques such as CAFCR [54]. We also applied techniques to support the participants in *grasping complexity*, such as Gigamapping [76].

Furthermore, we applied a variety of means to *enable creativity* and support creative thinking. Human-centric approaches, such as design thinking, emphasize creativity to explore innovative concepts [25]. Firstly, the sessions applied engaging and creative techniques, such as brainwriting [75]. Secondly, the sessions applied time constraints using timeboxes [53] to push the participants to engage and create. Thirdly, the timeline combines individual and group exercises to ensure all participants share their perspectives and build on each other's ideas and thoughts. Paulus et al. [57] emphasized the importance of combining individual and group exercises to enhance creativity. Finally, the sessions applied *visualizations* to stimulate creativity, either in the form of collective creation of sketches or preparing visualizations before the session. Kerzner, Goodwin, Dykes, et al. [79] highlighted the importance of visualization in creative workshops.

RQ2: How may the systems engineers apply co-creative problem solving in an industrial setting? Building on the findings from exploring the nine sessions, we realized a method consisting of a three-stage process and the timeline to support the systems engineers to achieve the capabilities in the industry case. The three stages are an understanding of the upfront problem and need, session planning, and the actual session, while the timeline combines five main tasks for a structured problem and solution exploration. Furthermore, the timeline aims to create a collective understanding and shared ownership of both the problem and solution space.

The method splits the roles of the problem owner and the facilitator. Paulus et al. [57] and Muller [52] described a similar approach for creative groups and workshops. The problem owner holds the system's insight and need for progress on the problem and has the incentive to take on this role. The facilitator leans on the problem owner for support during the session to share knowledge of the problem. Furthermore, the method makes use of brief sessions using inexperienced facilitators. The systems engineers in the industry case lacked facilitation experience, and shorter sessions are often easier to facilitate than full-day workshops. Using internal facilitators may also enable free discussions without confidentiality issues and avoids expensive facilitators who do not hold the necessary systems knowledge. Facilitation skills are not necessarily that common among engineers. However, this may vary in different organizations and cultures. We foresee the need for more experienced facilitators when including external and unfamiliar stakeholders such as customers. Conducting brief sessions with a few familiar participants may provide un-trained facilitators with facilitation experiences in a safe environment.

While exploring sessions, we experienced stakeholders reluctant to attend more extended sessions due to practical reasons such as lack of cost account and busy workdays. Aiming to cope with such practicalities, we strived to balance an acceptable session length in the industry case with the time needed to gain valuable insight through the timeline. We found sessions with a duration of about two hours to provide valuable outcomes when planned well, including about six participants familiar with the session context. Sessions including several participants unfamiliar with the session context may require a longer time.

RQ3: What may be the main challenges for the systems engineers to adopt co-creative problem solving as a new way of working? After realizing the method, we applied it in the industry case in two sessions, Sessions A and B, for an initial evaluation. In Session A, we found the method supported the systems engineers in planning and conducting a structured problem-solving session with stakeholders. In Session B, we observed the facilitator and the problem owner failing in the upfront planning, resulting in a session with participants mainly talking. In both sessions, the facilitator and the problem owner strived to include participants holding the needed knowledge for early validation of essential aspects such as business case, value proposition, and enabling technology. Due to the context of the industry case, we could not include external stakeholders, such as customers. We would have liked to include external stakeholders to evaluate how the method supports systems knowledge through co-creation with beneficiaries such as customers or users. The problem owner and the facilitator need to consider the necessity and possibility of customer inclusion during planning. When observing the systems engineers applying the method without interference from the researchers, we found that they neglected creative thinking during planning. In Session A, they did not include the individual exercise. In Session B, they failed to plan for a creative problem-solving exercise. The problem owner and the facilitator appreciated the method's ability to plan and structure the session. They stated that they missed using a creative exercise in debrief of Session B.

McFadzean found the usability of a method focusing on collective creativity in engineering teams dependent on the participants' willingness and ability to engage in such activities [23,24]. This way of working is unfamiliar to some people and challenges their comfort zones and their perception of acceptable ways of working. Setting session rules or informing participants upfront of what creative problem-solving techniques are may support people to feel less uneasy and prepare for engaging in this new way of working. While exploring the sessions, we observed that once the participants familiarized themselves with creative problem-solving techniques, most seemed to approve and appreciate this way of working. McFadzean [23,24] proposed a framework to ease the selection of techniques based on needs and level of experience. We propose to make use of McFadzean's framework [56] as a guide during session planning. By gradually building experience in using co-creative problem solving, we expect the effectiveness of the method to increase. Jones [7] emphasized the importance of continuity and investment in this way of working to provide insight into complex problems. Following the recommendations by Jones, we propose a systemic use of the method to enhance co-creation between systems engineers and stakeholders and support a long-term outcome.

7.1. Contributions to Theory

This article contributes to the body of knowledge by extending co-creation in systems engineering and proposes an industrial-relevant method for systems engineering to apply co-creative problem solving. We identify and define three main capabilities for co-creation in systems engineering to support rapid learning of systems knowledge in a context of socio-technical complexity. By exploring and scoring co-creative sessions in the industry case, we gain insights into achieving the capabilities in an industrial setting. We map the formerly identified success criteria to the capabilities and propose that these criteria can be means for future validation.

7.2. Implications for Practice

The proposed method indicates partial support for the systems engineers in an in-depth understanding of the problem and a structured problem and solution exploration. In the context of a mature Norwegian high-tech industry accustomed to efficiency and risk aversion, we foresee the method supporting this industry in exchanging knowledge and perspectives leading to rapid learning of systems knowledge and early validation of systems design. Thus, the method offers a step towards innovations that create value for beneficiaries such as customers, users, and businesses.

8. Conclusions

Guided by eight success criteria, this article explores co-creative problem solving through nine sessions in a real industry case. Furthermore, this article identifies and defines three main capabilities to provide rapid learning of systems knowledge in the concept phase towards innovations. These capabilities are problem and solution exploration, collective creation, and creative thinking. Building on the findings from exploring the nine sessions, we propose a method to support systems engineers using a three-stage process and a timeline for conducting co-creative sessions to achieve the capabilities. Our findings from an initial evaluation imply that the method partly supported the systems engineers in a structured problem and solution exploration focusing on multiple perspectives and shared ownership. Furthermore, our findings imply that the main challenges in applying the method are the systems engineers' experience in using creative problem-solving techniques and the willingness to engage in such activities.

Previous research on co-creation includes value co-creation in the marketing domain and co-creation in other domains such as design, focusing on collective creativity between designers and stakeholders (co-design). This article aims to extend co-creation in systems engineering to support systems engineers in rapid learning of systems knowledge to cope with complexity in systems development. Collaboration and creativity have been found to be essential in systems development, such as during concept evaluation and systems synthesis. However, co-creation in systems engineering is less explored. This article looks towards systems and design practices and proposes a co-creative method between systems engineers and stakeholders. The method enables the exchange of knowledge and perspectives and offers a step towards innovations that create value for beneficiaries such as customers, users, and businesses.

Limitations and Future Research Directions

Action research forms the basis of this research in a longitudinal study of about two years within a development team in the concept phase of an innovative complex system of systems. Action research and similar participatory approaches are applied in research on systems engineering to gain an in-depth understanding of industry challenges and improve. However, these research approaches increase the risk of researcher bias and challenge the generalization of research results. We strived for valid research results by focusing on triangulation and rich data collection.

We focused our research primarily on one industry case. Hence, we cannot claim that our findings nor the proposed method fit other contexts and needs than described in this article. Due to the context of the industry case, we could not include external stakeholders in the initial evaluation of the proposed method. We propose further research to evaluate how the method support rapid learning of systems knowledge by including external stakeholders such as customers or users.

Based on our research, the company established a new work process for their innovation projects, including the proposed method. The willingness to adopt the method in the industry case indicates that the systems engineers found the method valuable and aim to continue to use it. However, we need further research over a longer time to fully evaluate how such a method supports the systems engineers to achieve the identified capabilities. We propose to continue the use of the success criteria as means for future validation.

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Appendix A

Table A1 provides an overview of the statements and the NPS scores in the survey used in S1 to S5. The leftmost column shows the success criteria (SC) that the statements derive from. The rightmost columns indicate the most significant promoters and detractors in bold (NPS ≥ 3, NPS ≤ -3).

Table A1. NPS scores of statements for S1 to S5.

SC	No.	Statement	NPS				
			S1	S2	S3	S4	S5
8	Q1	This session made me focus on the user	−1	−3	2	−1	1
6	Q2	This session made me focus on the customer	−2	0	0	1	−3
2, 7	Q3	We discovered new relations in this session (such as a broader understanding of a problem or challenges)	2	2	1	−2	−1
2	Q4	We discovered unknown unknowns (things we did not know we did not know)	0	0	−1	−1	−2
4	Q5	The session enabled all participants to contribute with their knowledge and ideas to the discussions	2	4	−1	3	2
4	Q6	The session helped to understand and share different perspectives	1	4	3	3	0
3	Q7	We discussed business potential in this session	−3	−5	0	1	−1
9	Q8	A structured session was beneficial for the outcome of this session	1	2	-	-	0
7	Q9	We were creative together and got new ideas	1	0	1	1	0
9	Q10	The outcome of this session will contribute to project progress	1	2	1	0	0
9	Q11	This session covered our need at this point in time	0	−1	0	−3	0
5	Q12	Visualizations used in this session enabled us to have valuable discussions	1	−1	0	−1	1
6	Q13	This session enabled us to validate customer needs	−1	−2	−1	−1	−2
8	Q14	This session enabled us to validate user needs	1	−2	−1	−1	1
1	Q15	This session enabled us to push ideas and/or concepts to the limits	1	−3	0	−2	−2
1	Q16	We disregarded some ideas and/or concepts during the session	−1	−3	−1	−3	−2
9	Q17	The outcome of this session was worthwhile the effort	2	2	0	-	0
1	Q18	This session helped to reduce risk early	1	2	−1	−3	−1
-	Q19	Please list your 3 top benefits from this session (open-ended)					
-	Q20	Please list your 3 top concerns from this session (open-ended)					
-	Q21	Any other thoughts? (open-ended)					

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