What can (Systems of) Systems Engineering contribute to Oil and Gas? An illustration with case studies from subsea.

Gerrit Muller
NISE
HSN
Kongsberg, Norway
gerrit.muller@usn.no

Kristin Falk
NISE
HSN
Kongsberg, Norway
Kristin.falk@usn.no

***Abstract*—The oil and gas industry see the potential of using systems engineering, given the complexity of the domain. Actually, oil and gas systems are systems of systems by nature. The domain will need to adapt systems engineering methods and techniques to their specific circumstances and needs.**

This paper presents a set of examples of research projects, which evaluate specific methods or techniques in the oil and gas domain. A large number of these studies will help the domain in adapting the body of knowledge of (systems of) systems engineering to oil and gas.

Keywords—oil and gas, systems engineering, systems engineering management, architecting, evaluation

I. Introduction

At the INCOSE symposium in Edinburg in July 2016 Shell and GE kicked off an INCOSE working group Oil and Gas. This working group prepared presentation material explaining the value of systems engineering for this domain. This paper uses the working group material as foundation.

The Norwegian Institute in Systems Engineering (NISE), part of the university college of Southeast Norway, has been cooperating closely with several companies in the oil and gas industry. This cooperation included teaching, research, and consultancy. This paper reports NISE's experience of applying systems engineering in subsea Oil and Gas.

Oil and Gas subsea production systems are systems of systems consisting of many interacting constituent systems. Fig 1 shows an artist impression of such production systems.

Fig. 1. Illustration of subsea production systems at different sea depth levels.

Sec II shows the value that oil operators see in systems engineering and why. Sec III explains NISE's education and research model. Sec IV shows results in Systems Engineering Management, while Sec V shows results in Architecting. Sec VI provides a discussion and concludes the paper. Finally, Sec VII indicates future research.

II. Why Oil and Gas Operators See Value in Systems Engineering

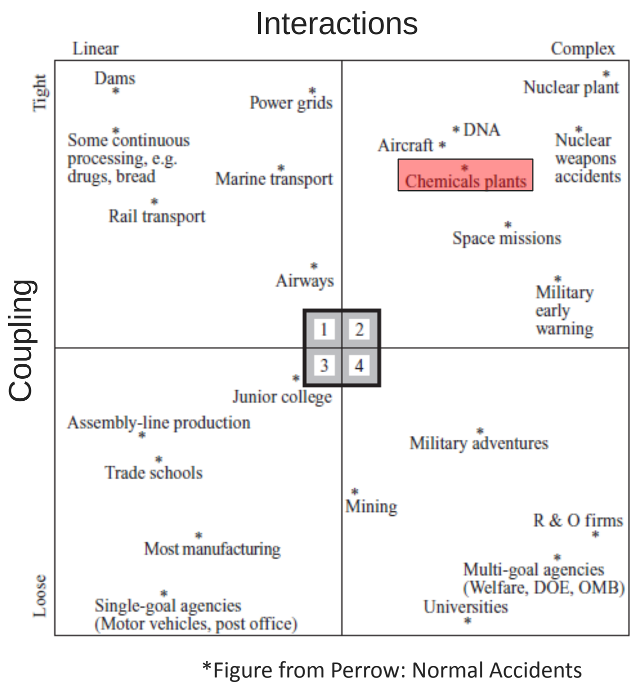

Fig. 2. The figure that Vice Presidents at oil and gas operators used to explain that owners of comparable complex systems use systems engineering.

At the kick off meeting of the Oil and Gas working group in Edinburgh, vice-presidents of the oil operators showed how they had used Perrow's figure in Normal Accidents [1] to explain the need for systems engineering in their companies and domain. Perrow's figure shows various types of systems in 2 dimensions:

coupling from loose to tight and interactions from linear to complex. The vice-presidents at oil operators used this figure, see Fig 2, to explain that other system domains with similar coupling and interactions use systems engineering to cope with complexity, while the oil and gas domain barely uses systems engineering.

The working group makes a call for change that we paraphrase here:

The oil and gas operators have been building these large systems with success, however:

- ***Cost** has increased significantly*
- ***Quality** escapes still persist across the industry*
- ***Schedule** for delivery has increased significantly*

O&G currently practices several SE methodologies; however

- *Subsea developments have gotten increasingly **more complex** due to higher pressure and temperatures*
- ***Lack of traceability** from requirements to the product installed*
- ***Reliance on people with decades of experience** to design, build, install, and operate their equipment.*
- *Every operator and every supplier has their own **unique ways of engineering** their products. There is no industry regulatory authority.*
- *This is leading to **inconsistent**, **incompatible** designs that frequently **do not meet the requirements or stakeholder needs** without significant and extraordinary efforts by all parties*

O&G is missing a methodology to consistently produce an output from project to project with differing staff….So, how much SE is needed?

One of the challenges of introducing systems engineering is to have a proper amount of systems engineering. The working group quotes Honour's PhD thesis [2], stating that about 15% of the program cost is the optimal amount of systems engineering.

III. EDUCATION AND RESEARCH MODEL IN SYSTEMS ENGINEERING

NISE, as part of the University College of Southeast Norway, is located in Kongsberg. Kongsberg is a small town with about 26 thousand inhabitants. This small town is the hometown for a wide variety of companies employing about 9 thousand engineers. Local and national government and industry identified systems engineering as strength of the industry and as strategic important. In 2006, these three parties started the Norwegian Center of Expertise in systems engineering. One of the first result of the center of expertise was the start of a master study in systems engineering [3].

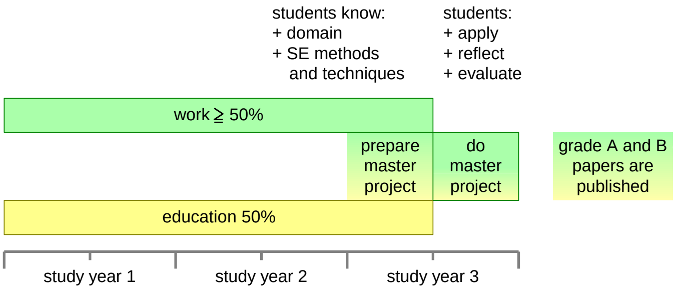

Fig. 3. Stduy model of the three Industry Master in systems engineering

Fig 3 shows the study model of this master study. Main characteristic is that students work and study concurrently for three years. Industry offers three-year part-time positions to facilitate this model. During the first 2½ years, the students follow 11 courses. Each course consists of one week of intensive training followed by a 10-week homework assignment. Students also follow a course called Reflective Practice [4] in the form of 9 workshops plus a small project. The goal of Reflective Practice is to help students in connecting the theory they learn at school with the practice they experience at work. Lastly, they do their master project in the company for 6 months.

In the master project, students apply some of the theory they have learned to reflect and to evaluate the theory. These master projects are a valuable research vehicle. Each year, we have about 25 students with background knowledge in the company and theoretical knowledge of systems engineering researching the effectiveness of the theory. We publish about 20% of themaster project papers[1].

Fig 4 visualizes the master project process [5]. The preparation takes place in three steps:'

- initial thinking and exploration starting in the second study year
- preparation with the coordinator
- final preparation with the academic supervisor

The student is responsible for shaping the master project proposal and the master project approach. The proposal shapes and defines the project such that the company is willing to fund the project, since it is sufficiently relevant for them. The academic supervisor helps to shape the academic approach and contribution; in this phase, the student fine-tunes the topic and scope together with the academic supervisor. The academic supervisor aligns the proposal with the NISE research agenda. The master project coordinator facilitates the preparation and execution with a number of workshops, shown as triangles in Fig 4.

[1] All published master project papers are at http://gaudisite.nl/MasterProjectPapers.html

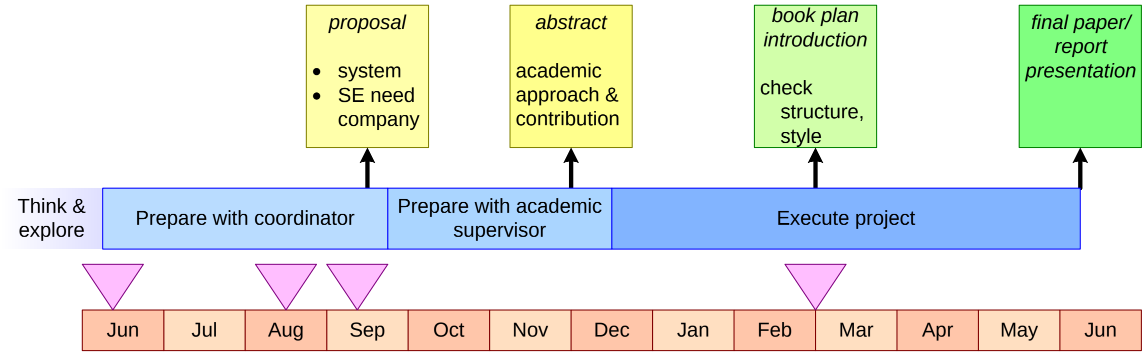

Fig. 4. Timeline of the master project.

	all oil&gas master projects	published
Concept Selection	13	4
Conceptual Modeling	9	2
Requirements	9	1
Systems Integration	8	1
A3	6	1
Knowledge management	4	1
Interface Management	4	0
MBSE	4	0
Systems Design	4	0
Needs Analysis	3	1
Risk Management	3	0
Late Design Changes	2	2
Tolerance Management	2	2
Decision Making	2	0
Documentation	2	0
Functional Design	2	0
Project Management	2	0
Taguchi	2	0
Autonomous	1	1
ConOps	1	1
Enterprise Resource Management (ERP)	1	1
Lifecycle Management	1	1
Qualification	1	1
Trade study	1	1
Others	12	0

Fig. 5. Analysis of keywords of master projects in oil and gas

In the Oil and Gas domain, 80 students did their master project in the period 2009 to 2017. We published 15 of these 80 papers. We analyzed the main key words of these papers, using one or two keywords per paper. Fig 5 shows the most occurring keywords. From the analysis of all projects, we see that the topics *concept selection*, *conceptual modeling*, *requirements*, *systems integration*, and *A3s* are the most popular. Students select their topic by looking for relevance for their company and ongoing company project, their own affinity, and their academic supervisor's (research) interest.

NISE staff coaches the students in the half year before the master project starts in selecting and shaping the master project topic. We see in this process, that managers and students typically propose the topics requirements engineering, interface management, and supply chain management. These topics form the foundation for systems development and deployment, together with many more systems engineering management related topics, such as product lifecycle management, configuration and version management, and release management. Students themselves often come up with topics like concept selection, MBSE, and SysML. These topics are means or solutions. In the beginning, students often are not able to explain what problems these solutions solve (we call this the hammer syndrome; the owner of a hammer may try to solve any connection problems by using mails and hammer).

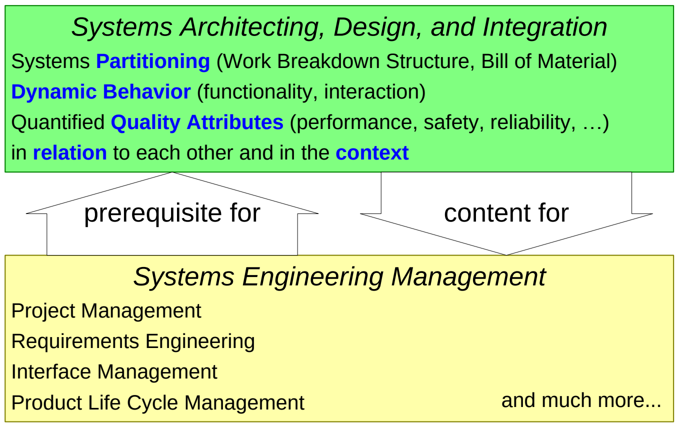

Fig. 6. The relation between systems architecting, design, and integration and systems engineering management

The academic staff has research interests related to systems architecting, design, and integration. Fig 6 shows that systems engineering management forms the foundation of systems development, while systems architecting, design and integration covers the "content". The content is the understanding of problem and solutions, how, and why they work.

In next sections, we will illustrate both systems engineering management and architecting with a few master projects in oil and gas.

IV. SYSTEMS ENGINEERING MANAGEMENT

A. Requirements Management

Requirements management scores high in any conversation about systems engineering in oil and gas. Wee applied a requirements management tool [5].

Wee's initial analysis of requirement inputs for the workover system makes clear why this topic is so hot in oil and gas see Fig 7. For this system project, he counted 112 input documents from the following main sources: The Norwegian Petroleum Directorate, Client specifications, the company itself, Norwegian standards, ISO standards, and other sources. The amount of inputs and the amount of resulting system requirements is high.

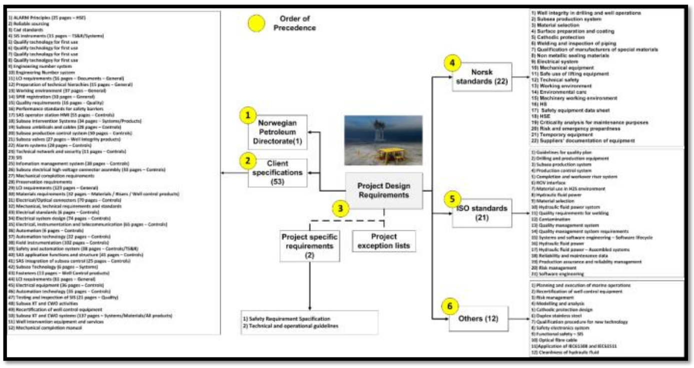

Fig. 7. Wee's analysis of requirements inputs for a workover system.

Another finding of Wee is that

- the requirements tend to be vague and ambiguous
- the operating conditions are unknown
- requirements prescribe solutions

These problems are pervasive throughout all inputs. The requirements are of poor quality, violating all systems engineering theory on requirements engineering.

It is no wonder that the oil and gas domain jumps onto requirements management, given the state of affairs with (too) many inputs and requirements of poor quality.

B. Interface Management (IM)

Nilsen analyzed the cost growth that the study attributes to insufficient Interface Management [6]. Nilsen's research uses a set of Varying Order Requests (VOR) and related IM Activities data between the SPS contractor and others including Drilling, Topside, and Installation (SURF) Contractors. As Fig. 8 indicates, the Drilling contractor has the largest scope, while the SPS contractor often needs to adjust its interfaces to the others.

Detailed analysis of 750 VORs and more than 12 000 IM activities for one project concluded "Early involvement of contractors and IM could help avoid 29% of formal changes and reduce project cost growth by 18% for the client." The qualitative in-depth interviews supported this also for six of the seven other projects in this study.

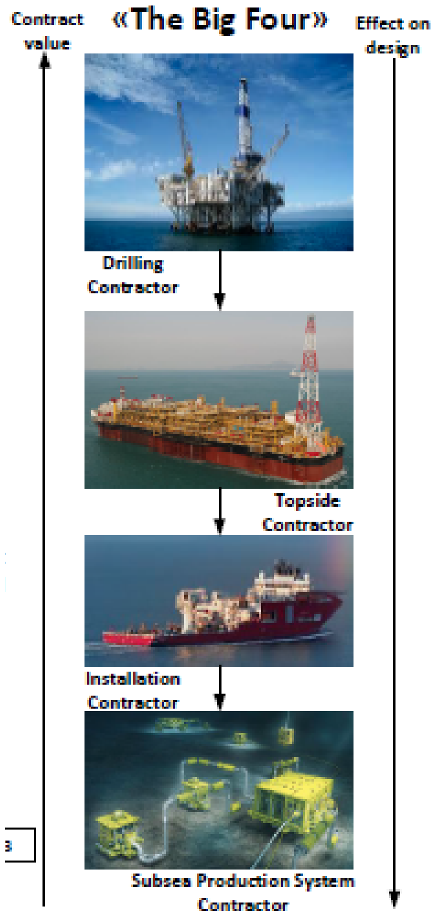

Fig. 8. Main contractors.

The quantitative analysis shows that IM is central in engineering endeavors, and has the potential to mitigate project cost growth. Based on these findings, the researchers conclude that establishing IM processes between all parties during the FEED (Front End Engineering and Design) stage would have a significantpositive impact in avoiding cost and schedule slips during project execution. This research also indicated that an integrated SPS and SURF contract award could yield potential savings and risk reduction for oil and gas companies.

V. ARCHITECTING

A. Needs analysis

Tranøy analyzed where cost overruns in Engineering, Procurement, and Construction (EPC) contracts come from [7]. In their company, scope changes and late design changes were main cost drivers. He analyzed the amount of effort spend on systems engineering and used Honour's data on the value of systems engineering as benchmark [2]. The conclusion is that the company spends sufficient effort in systems engineering. Further analysis identified a lack of understanding of operational needs as root cause for scope changes and late design changes.

For the analysis, Tranøy used the registration of variation orders. Experts determined in reviewing the variation orders that

- 74% of the VO's were preventable by need analysis

- 92% of the cost incurred by late design changes, were preventable

B. A3 architecture overview

Four students in the conceptual modeling course used a workover system as case. After the course, the students and teacher transformed the result in a publication [8]. This study uses the A3 Architecture Overview (A3AO) as proposed by Borches [9] [10]. A3AOs combine a few essential ideas:

- The A3 paper size (297 x 420 mm) forces authors to capture the essence
- The format prescribes the combination of multiple views, especially physical, dynamic behavior, and quantifications
- The format promotes visualizations (e.g. diagrams, graphs, images)
- Borches original template uses a two-sided A3 with a graphical side and a textual side; A single sided graphical variant is used more often nowadays

The four students working at two competing companies elaborated the case in a 20-slide PowerPoint presentation, which we later used to create an A3AO as shown in Fig 9.

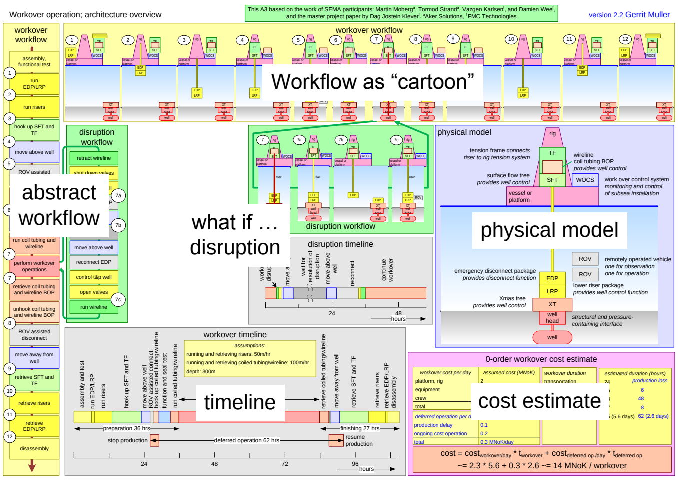

Fig. 9. A3 architeture overview of a workover system.

The A3AO shows on top a workflow as a “cartoon”. This is a highly visual representation of the workflow. This visual workflow communicates better with designers from the physical domain, such as mechanical engineers, than a more abstract workflow. The dynamic nature of the workflow facilitates reasoning about the operational use, providing insight in operational needs. The authors used the abstract workflow to create a timeline of the workflow operation. This timeline serves as input to a cost estimate. Most of the A3 shows the “happy flow” model. In the middle of the A3 an example of a disruption is added: what happens if a storm disrupts the workover operation?

This A3AO captures the entire workover system, the way it is used, the impact on the duration of the workover operation, and the cost of it, all on a single A3. The visual format is highly accessible for diverse stakeholders. The level of detail facilitates overview and reasoning at “what if” level.

C. Concept selection and Concept of Operations

Solli applied a Pugh matrix for concept selection in combination with an illustrated Concept of Operations (ConOps) [11]. In the problem analysis, he mentions late identification of operational needs and a lack of knowledge transfer as problems, which Pugh matrix and illustrative ConOps will address.

In the course of the project, he identifies four alternative concepts, shown in Fig 10. He describes the use of a Pugh Matrix for concept selection as:

- *Multi criteria decision making method in matrix format.*
- *Allows for comparison of multiple design candidates towards a set of criteria.*
- *Communicates the main characteristics of the proposed system.*

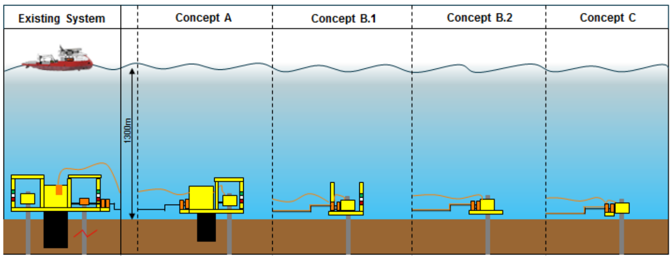

Fig. 10. The existing system and the four alternative concepts.

As next step, he made an illustrative ConOps too:

- *Create a common understanding of the concepts amongst project personnel and stakeholders.*
- *Gather and display known vital information in a comprehensible way.*
- *Act as an early validation of the concepts.*
- *Reveal operational needs.*

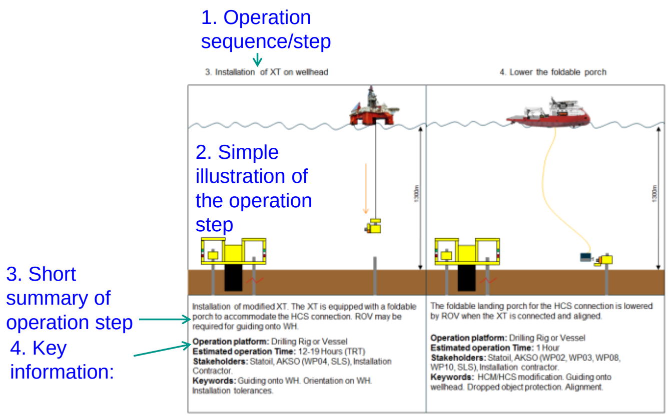

Fig. 11. Two steps from the illustartive ConOps

The illustrative ConOps is similar to the cartoon of the workflow, see Fig 11. However, it adds more information, turning it into a more complete ConOps. The format is still schematic with the focus on the essence of the concept and its operation.

Finally, the study achieves a concept selection with an extensive and insightful Pugh matrix; see Fig 12.

User input

	Criteria	Priority setting	A Simplified Snefrid	B.1 PGB with Toast rack	B.2 PGB with GP's	C Satellite XT on WH
Cost	Hardware Cost	High	2	3	4	5
Cost	Installation Cost	Standard	2	2	3	4
Cost	Operational Cost	Standard	3	3	3	3
Design	Engineering hours (Amount of new engineering, re-use, analysis)	Standard	5	3	3	2
Design	Design familiarity (Is the design known in AkSo? Previously delivered?)	Standard	4	2	3	3
Design	Requirement compliance	Standard	5	4	3	2
Design	Deliverytime from call-off (Long lead items, fabrication time)	High	3	3	3	4
Design	Amount of new qualifications (TQP's)	High	5	2	2	2
Design	On-shoreTestability (Availability of necessary equipment and procedures)	Standard	4	3	3	4
Installability & Retrievability	Number of installation runs required	Standard	1	2	2	5
Installability & Retrievability	Installation time	Standard	1	2	3	4
Installability & Retrievability	Weather vulnerability (Metocean constraints, Hs)	Low	2	4	4	4
Installability & Retrievability	Need for special tools	Low	4	3	3	3
Installability & Retrievability	Guide system robustness	High	4	4	3	2
Installability & Retrievability	Size of vessel required (Rig, heavy lift vessel, installation vessel)	Standard	1	2	3	5
Installability & Retrievability	Weight & Size	Standard	1	3	4	5
Installability & Retrievability	Retrieval flexibility of equipment	Standard	3	4	4	2
Operability	ROV access	Standard	3	4	4	4
Operability	Flow assurance (Hydrate/Scale, pipeline friction, pressure bleed-off)	Standard	3	3	3	3
Operability	Dewatering & start-up (Service access, injection points, etc.)	Standard	3	4	4	4
Operability	Reliability	Standard	3	4	4	4
Operability	Interchangeability	Standard	5	2	2	1
	Indicating summary:		78	74,5	78,5	84,5

The concepts listed are ranked on a scale from 1-5 based on their attributes for each criteria. 3 is the mean value and describes a good enough performance to the criteria. A higher number shows a better performance, while a lower number shows a worse performance on the criteria listed.
The priority setting enables you to prioritize individual criteria to a higher or lower importance. If the priority is set to low for a criteria, that criteria will count less compared to a standard or higher prioritized one.

Rating	Description
1	Unfavorable performance
2	Less than satisfactory performance
3	Satisfactory performance
4	More than satisfactory performance
5	Excelent performance

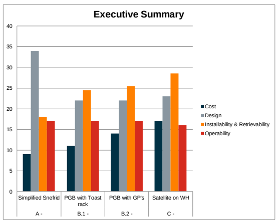

Fig. 12. The final Pugh matrix for concept selection

VI. *Discussion and Conclusions*

We have shown five examples of master and course projects that resulted in publications. Two examples addressed systems engineering management, covering requirements management and interface management. Three examples addressed systems architecting, design, and integration, covering operational needs analysis, A3 architecture overviews, ConOps, and concept selection. Up to 2017, we had 10 more publications and 60 more not-published case studies in the same domain.

We assert that this type of research based on Industry-as-laboratory [12] stepwise creates insight in when what methods, techniques, and tools work. Each individual case study is an incident without any possibility to generalize. However, frequent repetition of similar studies will help to see reoccurring patterns, which is the start of theory forming.

An example of a topic where we have a growing amount of publications is concept selection. The publications [13], [14] [15], and [16] are four more publications on concept selection, where [13] reports on four studies.

Since oil and gas is a complex domain (Fig 2), it may benefit from methods and techniques that have been beneficial in other domains. However, when taking over such methods and techniques, the oil and gas domain needs to adapt them to the specific domain needs and circumstances. For example, blindly copying requirements management tools from for instance defense may be disastrous, due to the heavily polluted requirements input.

In the case studies, we see in general that simple means, e.g. methods that can be applied with low effort, such as writing SMART requirements, using interface management, Pugh matrix for concept selection, illustrative ConOps, and A3AOs are effective and help in achieving better solutions faster and more reliable. We argue that this translates into less cost overruns and delays.

Studies like the examples in this paper may help the oil and gas domain in the adaption process of methods, techniques, and tools.

VII. Future Research

Many more of these type of case studies are needed to identify patterns. These patterns are useful in providing guidelines for effective use of methods and techniques in the oil and gas domain. That triggers the need for more research to evolve and validate such guidelines. Future research will benefit from aligning research methodology and data collection, since that will ease comparison and analysis across projects.

Studies over a longer period and larger scope will help to study longer-term effects and impact on the organization. For these larger studies, we may need PhD students or PostDoc positions.

References

[1] C. Perrow, Normal Accidents Living with High Risk Technologies, Princeton University Press, 1999.

[2] E. Honour, Systems engineering return on investment, PhD thesis at University of South Australia, 2013.

[3] G. Muller, „How to start a new Master Study in Systems Engineering?," in *INCOSE*, Rome, 2012.

[4] G. Muller, „Reflective Practice to Connect Theory and Practice; Working and Studying Concurrently," in *CSER*, Hoboken, 2015.

[5] D. Wee en G. Muller, „Evaluating the effectiveness of applying a Requirements Management System for a Subsea Oil and Gas Workover System," in *INCOSE*, Edinburgh, 2016.

[6] M. A. Nilsen en K. Falk, „Reducing Project Cost Growth Through Early Implementation of Interface Management," in *INCOSE*, Washington DC, 2018 (accepted).

[7] E. Tranøy en G. Muller, „Reduction of Late Design Changes Through Early Phase Need Analyis," in *INCOSE*, Las Vegas, 2014.

[8] G. Muller, D. Wee en M. Moberg, „Creating an A3 Architecture Overview; a Case Study in SubSea Systems," in *INCOSE*, Seattle, 2015.

[9] D. Borches en G. M. Bonnema, „Focusing architectural knowledge to support evolution of," in *INCOSE*, Chicago, 2010.

[10] D. Borches, A3 architecture overviews: a tool for effective communication in product, Enschede: PhD thesis, University of Twente, 2011.

[11] H. Solli en G. Muller, „Evaluation of illustrative ConOps and Decision Matrix as Tools in concept selection," in *INCOSE*, Edinburgh, 2016.

[12] C. Potts, „Software-engingeering research revisited," *IEEESoftware*, vol. 10, nr. 5, pp. 19-28, 1993.

[13] G. Muller, D. J. Klever, H. H. Bjørnsen en M. Pennotti, „Researching the application of Pugh Matrix in the sub-sea equipment industry," in *CSER*, Los Angeles, 2011.

[14] E. Hansen en G. Muller, „Set-based design - the lean tool that eludes us; Pitfalls in implementing set-based design in Kongsberg Automotive," in *INCOSE*, Rome, 2012.

[15] L. Lønmo en G. Muller, „Concept Selection - Applying Pugh Matrices in the Subsea Processing Domain," in *INCOSE*, Las Vegas, 2014.

[16] A. K. Bye en L. Piciaccia, „System Engineering Applied to Concept Design Optimization of Design Coolers," in *INCOSE*, Las Vegas, 2014.