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

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

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

I. INTRODUCTION

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

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

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

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

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

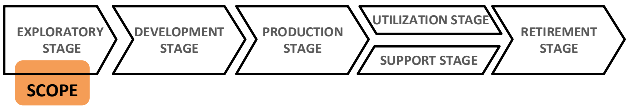

Fig. 1. System life cycle

II. RELATED WORK

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

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

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

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

III. CONCEPTUAL MODELS

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

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

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

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

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

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

IV. THE CASE

A. Research Method

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

B. A Short Introduction to Subsea

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

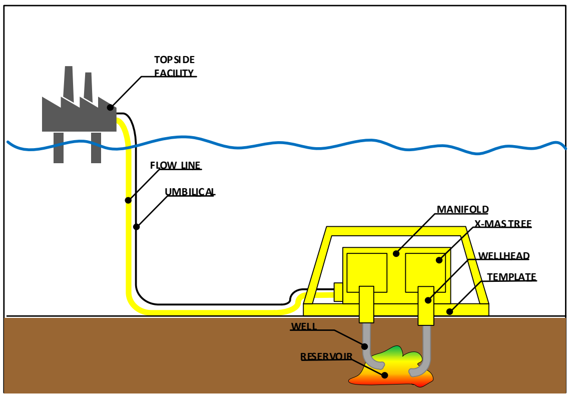

Fig. 2. Illustration of the subsea system

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

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

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

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

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

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

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

C. Introduction to the case

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

1) The field

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

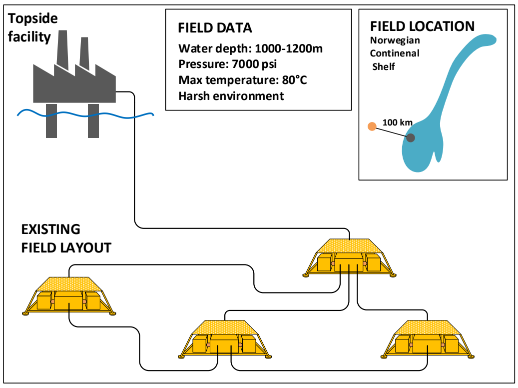

Fig. 3. Field data

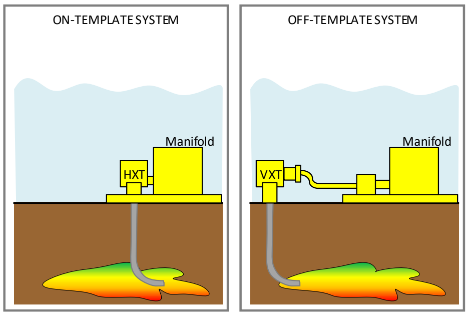

Fig. 4. Alternatives for field expansion

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

2) The study

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

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

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

D. Modeling

1) Identification of tension and issues

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

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

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

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

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

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

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

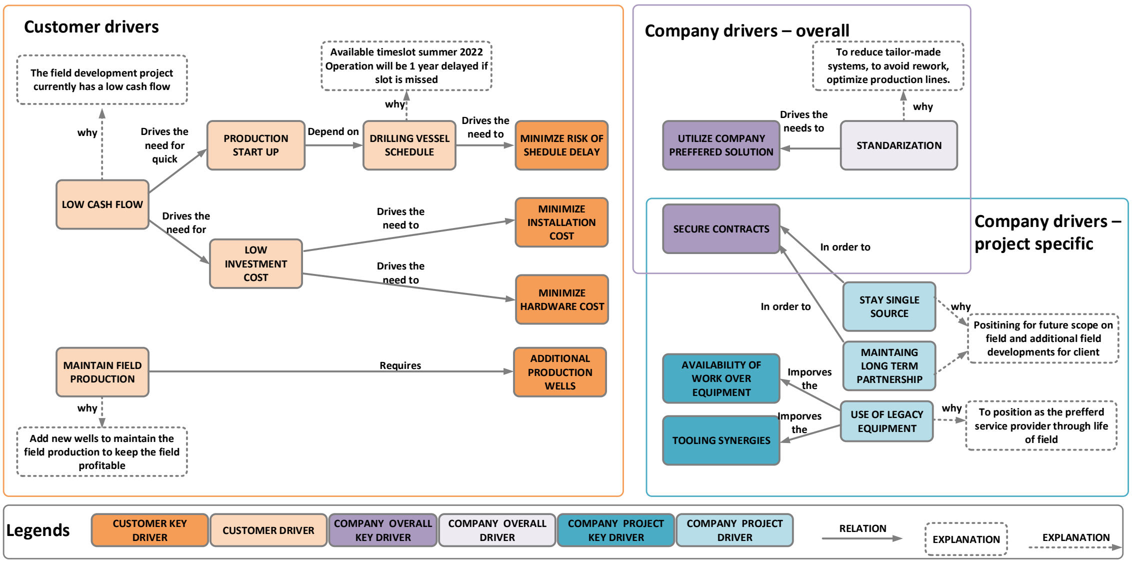

Fig. 5. Key driver mapping

2) Modeling of life cycle impact

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

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

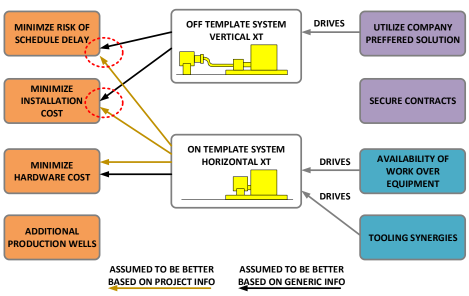

Fig. 6. Relation between key drivers and design concepts

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

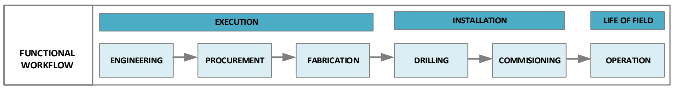

Fig. 7. Overall workflow - subsea system life cycle

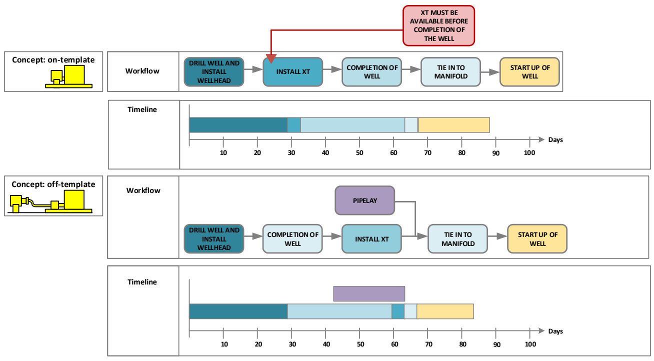

Fig. 8. Model - generic knowledge

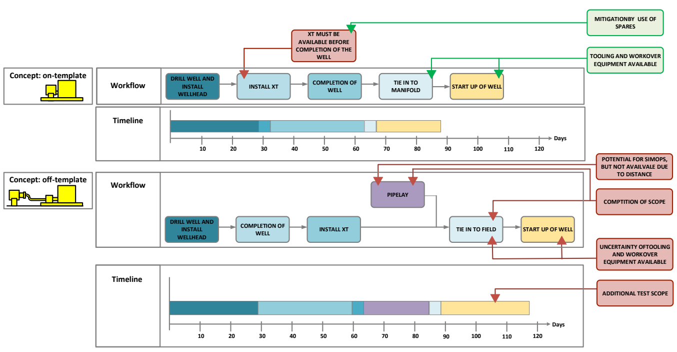

Fig. 9. Model - project specific knowledge

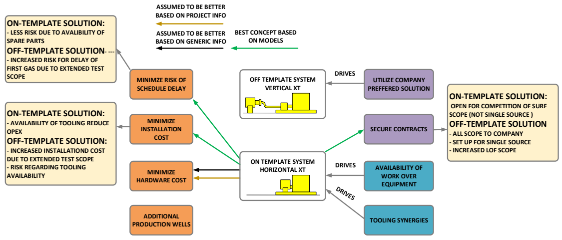

Fig. 10. Key driver map with findings from modeling

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

3) *Combining models for documentation*

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

V. Discussion

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

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

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

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

VI. Conclusion and Future Work

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

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

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