

Cause and Impact Analysis of Cost and Schedule Overruns in Subsea Oil and Gas Projects – A Supplier’s Perspective

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Abstract. This paper identifies drivers for cost and schedule overruns in subsea production system projects from a supplier’s point of view. Subsea Production Systems connects subsea wells to offshore vessels, and enable efficient and safe hydrocarbon production.

Using root cause analysis, cause and effect diagram, and Pareto charts in a specific company we identified three main drivers of cost and schedule overruns: qualification of products, changing vendors frequently, and project management.

Detailed analyzes of a reference project found that the supplier identified about half of the technology gaps during the tender phase. Technology qualification programs of key components were not included in the bid, although the project had to pay for related cost overruns. In summary, the project could have eliminated more than two thirds of the cost escalation related to qualification costs by capturing all technology gaps in the early tendering phase, and as a result significantly increased the profitability.

Introduction

Domain. Subsea production systems (SPSs) control and collect the flow of hydrocarbons from subsea wells to a floating offshore unit or to an onshore facility. SPSs are unmanned underwater systems that typically consist of subsea x-mas trees (valve arrangements), subsea manifolds, subsea templates, and pipelines (Figure 1). A control room on an offshore unit or an onshore facility controls the production



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

system.

Subsea field developments move towards new operational environments with increasingly deeper waters as new and more demanding geographical areas are explored. Harsh oceanic environment with low seawater temperature and high seawater pressure, combined with high-temperature/ high-pressure oil and gas wells, put great stress on the subsea equipment.

To operate in these environments, one can either modify existing technology or introduce new technology. Introduction of new technology may result in uncertainties and risks for suppliers, manufacturers, and operators/users. To reduce such uncertainties and risks, the new technology is qualified for its intended concept of operations (ConOps). According to the international certification body and classification society, DNV GL, qualification implies “providing evidence that a technology will function within specified operational limits with an acceptable level of confidence” (DNV 2011). The company in focus is an international supplier of equipment to the oil and gas companies. We have conducted the research within a Norwegian department specializing in subsea production systems. To avoid confusion of terms, the equipment supplier is hereby called “company”, and the oil and gas company are hereby called “customer”.

Case. In recent years, cost and schedule overruns in offshore oil and gas field developments have been getting attention from the media (Offshore.no 2011, Walls Street J. 2016, Petro Global News 2016, SOGM 2015), Norwegian entities and government (NPD 2015, NOU 1999), and oil and gas representative bodies (Oil & Gas UK 2015). Field developments are delayed for months and years, and development costs are higher than ever before. An extensive research study by Merrow (2012) analyses the performance of more than 200 oil and gas industry projects. The results show that 78% of all the oil and gas projects have an average of 33% cost overrun and an average execution schedule slip of 30%. A study by EY (2014) shows approximately the same numbers. In their study, EY found that 64% of all oil and gas projects face cost overruns and 73% of the projects experiences schedule slips. In addition to Merrow’s and EY’s research, the Norwegian petroleum directorate (NPD 2013) has evaluated five projects implemented on the Norwegian continental shelf. Their conclusion is in line with Merrow’s and EY’s research; there are considerable cost and time overruns in many of the projects.

Low oil price is also getting great attention, in addition to reports and media coverage on cost overruns and schedule slips. At the time we conducted our research, we had to go more than ten years back in time to see a similar oil price. The low oil price makes many field developments on the Norwegian continental shelf unprofitable. When combining low oil prices with cost increases, it is even more challenging to develop profitable oil fields. This forces the oil and gas industry to cut cost and increase efficiency through the entire value chain. Equipment suppliers must take their share, to reduce costs within their scope, in order to reduce the total cost of a field development.

Problem. As an equipment supplier, and as part of the value chain in the oil and gas industry, there is a need for the company to reduce cost and schedule overruns in their SPS projects. Lower cost and cost overruns of SPS deliveries may reduce the total cost of field development. And fewer schedule overruns may contribute to a shorter delivery time. Merrow (2012) and Media (Offshore.no 2011, 1,2) looks at reasons for cost overruns and schedule slips in a bigger picture, but they do not pinpoint the root causes. It is of interest to the company to identify areas to improve, in order to deliver projects more efficiently and at lower cost. Therefore, we look at the problem from the subsea supplier’s perspective. The aim of this research is to identify drivers for cost and schedule overruns in the supplier’s projects, by utilizing Systems Engineering (SE) tools and techniques. We use knowledge and experience provided by subsea experts within the company and an ongoing SPS project as a reference. The scope of supply of this project includes manifolds and various mechanical connection systems. The ongoing project is hereby named the “reference project” to anonymize the project and collected data.

Finding. A major finding from our research is that product qualifications are often done inside a delivery project, and that the tender team often fails to identify necessary TQPs in the tender phase.

This may negatively influence both the project execution schedule and the cost. The paper shows supporting data on the cost impact, but not directly on the schedule impact. We conclude that it is crucial to identify necessary qualification programs in the tender phase to deliver a product or system on time and at specified cost.

Background

SE Theory. To conduct our research we have applied SE theory and best practices from SE Body of Knowledge (BKCASE 2016) and the INCOSE SE handbook (INCOSE 2015). The SEBoK describes Systems, Systems Engineering activities, methods, principles, processes, and SE's interaction with other disciplines. The INCOSE SE Handbook defines the discipline and practice of systems engineering, and provides a reference to understand the content and practice of the SE discipline.

The SE body of knowledge also contains tools and methods to reduce cost and schedule overruns in projects. SE body of knowledge as well as research in the field of model based systems engineering (MBSE), (Korfiatis et al 2012 and Topper and Horner 2013) argue that MBSE improves communication among stakeholders, including customers, program/project management, systems engineers, developers, testers, and discipline engineers. The theory also states that system modelling may enhance knowledge capture and reuse of information. Well-crafted systems models may be viewed from multiple angles to analyze the impact of changes. SEBoK also argues that these benefits "have the potential to reduce time and cost associated with testing and integration of a system, and significantly reduce cost, schedule, and risk in commissioning a system". Furthermore, Johnsen (2009) describes how collaboration and relationship between customers and suppliers affect product innovation and development. It seems to be a consensus that close communication between these partners is positive for product development (Croom 2001, Nellore and Balachandra 2009, Wu and Wu 2015); it decreases cost and development time and increases product quality (Bonaccorsi and Lipparini 1994). Although this is applied in other domains, the subsea oil and gas business has a limited number of publications on the use of MBSE, and such tools were not included in the engineering process in the company when this research was conducted.

Tendering process in company. When oil and gas companies get approval from authorities to develop a petroleum field, they typically invite equipment suppliers to tender for the specific field development. During the tender phase, the equipment suppliers assess the tender documents, and offer a concept that is intended to fulfil the field operator's ConOps. The equipment suppliers with the best concept and cost efficient system will be awarded contracts. What is the "best concept" will vary between different oil companies. The two most important criteria are prize and technical feasibility. Other important issues are technology readiness level and earlier experiences with the supplier in terms of delivery time and quality.

When the company receives an *Invitation To Tender* (ITT), a tender team in the organization is mobilized. The oil and gas company/customer provides the tender team with requirement specifications along with the ITT. The company's concepts must satisfy this extensive set of requirements consisting of a detailed, text based "design basis" describing the solution, often down to the color and size of each component, and a large number of standards from API, Norsok, ISO and more. If there is a gap between what the customer asks for and what the company can offer, the company must communicate this. The company sends a clarification and gap list to the customer to communicate the identified gaps. A technical gap results in a TQP (Technology Qualification Program). In a TQP the system provider describes what type of qualification activities such as tests need to be completed prior to installing the system.

The tender team, consisting of three to four persons, has the responsibility for conducting the bid. The team has limited technical expertise, and is dependent on support from subject matter experts from all product and technical departments. Only the tender team can access the tender documents (requirement specifications etc.) received from the customer.

Usually, a tender phase lasts for three to four months. During this period, the tender team should know in detail what the tender documents and customer are asking for in terms of a desired

solution/system. This is a relatively short time for the tender team to acquaint themselves with all the documents.

Research Methodology

In our research we use basic tools of quality, namely cause and effect diagram (fishbone diagram) and Pareto diagram to identify and rank root causes. We also used the 5 *whys* methodology to dig deeper. Based on the first qualitative analysis, one particular project was analyzed quantitatively. At the end we researched two specific items within this project.

Root Cause Analysis. We have conducted a root cause analysis in the company organization to identify drivers for cost and schedule overruns in the company's SPS projects. The company is typically tendering 20 SPS projects per year, and has been running in the order of 4-10 projects simultaneously. Our analysis has been based on projects run over the last 10 years. Typical cost of a total EPC is in the range of 100-400 MUSD. They are the main delivery of this branch of the company. Ishikawa (1985) defined seven Basic Tools of Quality, a designation given to a fixed set of graphical techniques identified as being most helpful in troubleshooting issues related to quality. In our study, we have used two of these, namely Pareto Chart, and Cause and Effect diagram (also called Fishbone or Ishikawa diagram). The tools are called basic because they are suitable for people with little formal training in statistics and because they can be used to solve the vast majority of quality-related issues. The Seven Basic Tools stand in contrast to more advanced statistical methods such as survey sampling, acceptance sampling, statistical hypothesis testing, design of experiments, multivariate analysis, and various methods developed in the field of operations research.

Andersen and Fagerhaug (2006) described root cause analysis as "a collective term used to describe a wide range of approaches, tools, and techniques used to uncover causes of a problem". The purpose of the root cause analysis is to identify incidents and root causes that have caused internal or external schedule slips and associated cost increase in projects. We apply cause and effect diagram, also called fishbone and Ishikawa diagram (Ishikawa 1985) to capture, categorize and organize the identified incidents. The cause and effect diagram is a useful brainstorming technique to identify causes to a problem (Mehta 2014).

We did the root cause analysis in a workshop together with nine senior engineers with SE and discipline engineering backgrounds. The engineers all had been working in the domain for more than 5 years, and most of them for more than 15 years. There were three systems engineers, three reliability engineers, one flow assurance engineer, and two structural engineers. Each engineer has been working in ten or more projects relevant for this research.

These subsea experts have accumulated more than 180 years of experience within the field of subsea engineering and subsea production systems. To prepare the participants for the workshop, we asked them some days ahead of the workshop to reflect upon incidents they have experienced in projects they have been working with, and the underlying causes of these incidents. The reason for doing this was to encourage a diversity on input in the workshop. Then it would be less likely to lose good cases. A potential drawback with our approach could have been that the participants were biased prior to the workshop, but our experience did not indicate that this was the case. The workshop consisted of two parts:

- Part 1 Identification of incidents and root causes in projects that have caused schedule slips and cost escalation.
- Part 2 "Scoring" the incidents and root causes in terms of their impact on schedule slips and cost escalation.

We initiated the first part by introducing the participants to the problem of cost overruns and schedule slips. Then, we gave each participant a time slot to speak about their experience of incidents and causes to schedule and cost overruns in projects they have been a part of. Next, we had a joint brainstorming session where everyone could speak and discuss. The discussions were primarily

centered on the causes and root causes of the incidents identified by each of them. The objective with this part of the session was to identify root causes to all incidents.

In the second part, we wanted to identify the root causes with the biggest impact on schedule and cost overruns. We asked people to “score” the incidents and root causes in terms of their impact on schedule and cost overruns. Each workshop participant was given six notes: one with *HIGH (H)*, two with *MEDIUM (M)*, and three with *LOW (L)*. They placed the *H*-note on the root cause or incident they believe has the highest impact on schedule and cost overruns, and the *M*-notes on those they believe has slightly lower impact. This method is commonly used in the company for statistical and reliability assessments, and was proposed by one of the senior reliability. One reason for selecting this method was that it was familiar to the participants. A strength of this method is that the participants are forced to actively select the main drivers as they have only one “high impact” note each. A weakness of this method is that it relies solely on the participants’ opinions.

Note that the incidents and root causes that got an *L*-note still have a higher impact on schedule than those that did not get a note. This means that incidents and root causes without a score note have lower impact on schedule than the incidents and root causes that were given an *L*-note.

To determine which causes and incidents from the root cause analysis were the most critical, we applied a Pareto chart methodology, and calculated a total weighted score for each root cause. The purpose of the Pareto chart is to highlight the most important among a large set of factors. In quality control, it often represents the most common sources of defects, the highest occurring type of defect, or the most frequent reasons for customer complaints, and so on. Andersen and Fagerhaug (2006) suggest that high (*H*) is allocated a weight number of *nine (9)*. Medium (*M*) impact is allocated a weight number of *three (3)*, and the low (*L*) impact is allocated a weight number of *one (1)*. We calculated the weighted score by multiplying the total number of *H* with *nine*, the total number of *M* with *three*, and so on, and then summarized those numbers. We then plotted the total weighted score for the incidents and root causes in a Pareto chart (Figure 2). The Pareto chart displays graphically the degree of seriousness causes has on a problem, and helps identifying the most critical incidents and causes.

The root-cause analysis workshop captured incidents and high-level root causes. To get deeper insights into the identified causes, we used the principle of the “5 whys”-method.

5 Whys is an iterative interrogative technique used to explore the cause-and-effect relationships underlying a particular problem. The technique was formally developed by Sakichi Toyoda and was used within the Toyota Motor Corporation during the evolution of its manufacturing methodologies. The primary goal of the technique is to determine the root cause of a defect or problem by repeating the question “Why?” Each answer forms the basis of the next question. The “5” in the name derives from an anecdotal observation on the number of iterations needed to resolve the problem. Not all problems have a single root cause. If one wishes to uncover multiple root causes, the method must be repeated asking a different sequence of questions each time.

The method provides no hard and fast rules about what lines of questions to explore, or how long to continue the search for additional root causes. Thus, even when the method is closely followed, the outcome still depends upon the knowledge and persistence of the people involved.

We conducted the “five why” approach by speaking with personnel within the company. Conversations with experts in their respective fields gave us further insight into some of the identified incidents and causes to cost and schedule overruns. These people were product line managers and systems engineering managers and senior systems engineers. Even though it is not quantified information, it gives us a good picture of the situation and projects in the company.

Quantitative analysis of reference project. Based on the findings from the qualitative analysis we did a quantitative analysis on a specific reference project. We chose a typical SPS project that has been conducted during the last few years, and for which we had direct access to the project engineers. We analyzed the time and cost spent on the project as well as the plans. Due to confidentiality issues, we present the time and cost data in percentage only.

Results and Analysis

We present our most significant findings (top 3) from the root cause analysis in Table 1. The table displays how many “score notes” each incident/cause received, and their weighted score. Figure 2 shows a Pareto chart with causes and incidents, and their relative contribution on schedule slips and cost increase. Note that the Pareto chart plots only those causes and incidents that received a “score note” concerning their seriousness on schedule slips and cost increase. This is because the not-scored incidents will show no contribution on the chart. Table 1 and Figure 2 shows that *qualification of products in parallel with project execution* is the most critical cause of schedule slips and cost increase. Next is *frequent change of vendors*. The third is *project management/ execution methodology*.

Table 1: Results from the root cause workshop in organization.

No.	Incident/ Cause	Score			Weighted score
		# of H	# of M	# of L	
A	Qualification of products in parallel with projects	3 of	2 of	3 of	36
B	Changing vendors frequently	2 of	0 of	0 of	18
C	Project management/ execution methodology	1 of	1 of	2 of	14

It is interesting to note (from Table 1) that while eight of nine respondents rated A so highly, there is little agreement on its priority. Also interesting to note (see Figure 2) that there is such a steep drop-off in the number of respondents to the second and third causes presented here. This could indicate that there is little agreement about the nature and frequency of causes.

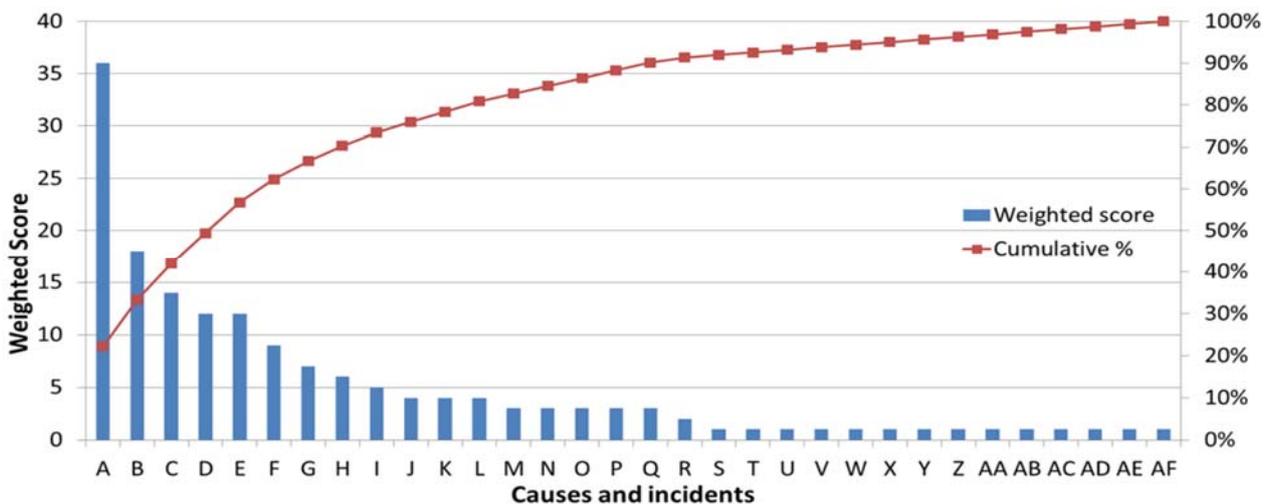


Figure 2: Pareto Chart of incidents and causes' impact on schedule slips and cost increase.

The above Pareto chart shows that we have a very diverse set of potential causes, none of which is responsible for a high percentage of problems. It is clear that we need to investigate the issue of product qualification more deeply. It may have been useful to conduct another survey to ascertain whether there is a relationship between product qualification failures and/or vendor changes or project management issues. There is a reason to believe that these three causes interacted significantly.

However, this was out of the scope of this paper.

For the readers' curiosity, the rest of the categorized causes and incidents (D-AF in Figure 2) are as follows:

- Longer fabrication time than planned
- Insufficient competence level and heavy internal systems in the organization
- Contractual issues
- Requirements and technical regulations issues
- Equipment failure/ issues
- Inadequate testing
- Engineering errors

The three last items on this list, namely Equipment failure, Inadequate testing and Engineering issues, were related to items that had already been qualified and applied in field, thus they were not included in the qualification category.

Through the root cause analysis, we found that Cause A, *qualification of technology in parallel with project execution*, is the by far the most significant cause of schedule slips and cost increases. It is worth noting that this is a relatively high-level root cause. In our research, we chose to go into details on this first cause (A). To refine our scope, we analyzed the number of qualification programs in one specific delivery project.

Analysis of Reference Project. We reviewed the reference project contract in order to identify the number of TQPs that was included in the bid, and in the initial project plans. Afterwards, we reviewed the latest documents available for TQPs, to compare to the bid. The number of qualification programs reflects the number of technology gaps the project faces.

The project contract states that the company identified **21** products in the tender phase that required a qualification program. Twelve of these were the company's own products, and **nine** of them were third party (sub suppliers') items. The latest documents on TQPs state that the company has identified **53** products that require a qualification program. 23 of these are related to company's products, and 30 are qualifications related to third party products. The project documentation reveals that many of these TQPs were identified 1-2 years out in the project execution phase.

We found that the number of sub supplier and company qualification programs has increased by 233% and 92%, respectively (compared to the bid). This revealed that sub suppliers' items contributed to a significant number of the additional qualification programs. This also means that several sub suppliers in the project have had unqualified products. However, we also discovered that third party items were often smaller qualification programs with less cost, and the most expensive qualification programs were the company's own.

We have not succeeded in getting our hands on qualification program schedules. A finding is that the qualification programs were run in parallel with the project, and are therefore not included in the project execution plan (schedule).

This situation makes it difficult to identify or prove whether qualification has caused delays. However, we have managed to get the actual cost for the TQPs and the estimated cost included in the tender. The aggregated total cost of all TQPs is several million USD.

Figure 3 presents different contributions to the actual TQP cost. In total 51 % of this actual TQP cost resulted from items that were not accounted for in the tender, while 49 % of the actual cost resulted from the 21 TQPs included in the tender. Going into details on the cost of the 21 tendered TQP's, we found that the estimated TQP cost (included in the tender) was only 27% of the actual TQP cost. Thus, only about one fourth of the actual TQP cost was budgeted in the original tender.

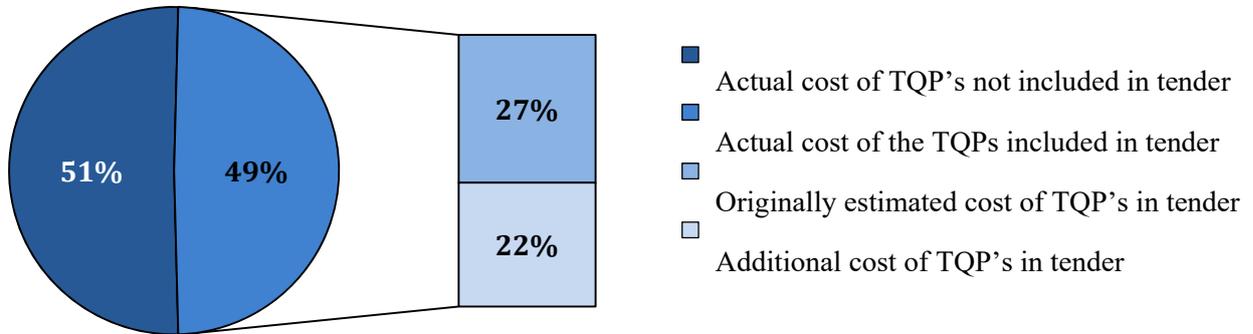


Figure 3: Actual and estimated TQP cost.

We were able to compare estimated qualification cost (that was included in the bid) with the total actual qualification cost. Our comparison showed that the total TQP cost has increased by 270%. The TQP cost for the 21 items included in the bid increased with 81%. We found that the additional TQPs contribute to 51% of the total cost, and 69% of the total *cost increase*.

To say it in other words, the bid team had identified slightly more than half of the cost associated with TQPs, and the project cost of the identified TQP's were more than doubled. We wanted to know why there were such large cost overrun, and did that by going deeper into the project.

Project specific examples. We researched the qualification programs for the manifold and connection system (MCS) scope of the reference project. In the bid, the MCS scope included four TQPs, one company TQP and three sub-supplier TQPs. The latest documentation reveals that the number is thirteen, of which four are from the company and nine from sub suppliers. We have reviewed the documentation for these TQPs. In addition, we have conducted unformal interviews with the lead engineer for the MCS scope on the reference project. We did this to gain further insight into why so many of the TQP were not included in the bid. Our investigation shows that the situation for some of the TQPs is quite complex.

Customer requirements differ from one field to another as no oil and gas fields are identical. According to the lead engineer, some components would always have some differences in functions or properties (material etc.) from field to field due to different requirements, and thus the components have to be re-qualified for each project. This means that use of an index like the Technology Readiness Levels described in API 17N must be executed with extreme care even at the highest TRLs.

Example 1: Key component. We have studied TQPs for a “Key Component” in the reference project. This “Key Component” contributes to almost half of the TQPs for the MCS scope. The “Key Components” are qualified for each project, and this is considered an “easy thing” to do. Moreover, the company does not produce these “Key Components” themselves. They are produced by sub suppliers. The “Key Component” is therefore a sub contract between company and a “Key Component” sub supplier. The customer (Petroleum Company) can be present while the testing is conducted, but this is not required. This is normally clarified between the company and the customer. It turns out that, since this is a sub contract between the company and a “Key Component” sub supplier, the TQPs are not formally included in the bid. They are not “forgotten”, but run in parallel with the project, as we have discussed earlier. However, since the cost is not included in the bid, the project budget does not include the qualification cost for these components. The project budget will

then suffer, because the project has to pay for the qualification programs, even though it is not included in the bid. This results in a cost overrun for the project. The customer may not see this additional cost in the first place, but the company will.

Example 2: Connection system. Another type of qualification program that was not included in the bid for the reference project was the qualification of a connection system. A customer requirement is that the connection system shall endure 40 *make and break* (M&B) cycles. *Make and break* is the cycle of connecting and disconnecting a pipeline with maximum momentum for which the connection system is designed. At the time of the bid, the company had qualified the connection system for 10 M&B. Unfortunately, the tender team missed this information. As a result, the connection system was deemed qualified. The issue was noticed later in the project execution phase. At this point, some of the equipment was already in production (manufacturing). The company requested to reduce the M&B cycles to 20, and got approval from the customer. However, the connection system did not pass the 20 M&Bs during the qualification tests.

To pass the test, the project introduced new material properties. The connection system now passed the tests. As a result, all the manufactured parts that were affected by this change had to be reworked with the new material properties. Some of the equipment had to be shipped back to a fabrication yard. Furthermore, most of the equipment was produced (with new material properties) when a new problem was discovered, the newly introduced material imposed other material issues. It was known that introducing the new material could impose other issues, but the project was under time pressure, and a decision to go with the new material was taken, as the risk was deemed acceptable. It was shown that the new material would pass all requirements and tests, but the project team did not consider subsea environment sufficiently enough.

Later, extended tests simulating subsea environment showed that the material would not endure the entire lifetime of the field that was specified in the ITT documents. As a result, new and more realistic tests in terms of how the equipment will be handled were developed, and tests of the initial material were conducted. The initial material passed the tests (with 20 M&B cycles). Then, all the manufactured equipment had to be re-worked once more, back to the originally applied material properties. The process of manufacturing, then re-manufacturing, and re-manufacturing once more, has entailed enormous costs. However, this is not documented in the cost for this TQP. The documented TQP cost for this qualification program is about 3.5% of the total TQP cost.

To dig further into why this TQP was not captured in the bid, we have interviewed a senior tender manager and a senior engineer in the company. The senior engineer has been responsible for the investigation of the described TQP (and others) and claims from the customer. They tell us that this particular TQP is a miss by the tender team. The tender team have not recognized that the system was qualified to 10 M&B. Therefore, they approved 40 M&B that the customer requested. It has been much back and forth to investigate why this could happen. The explanation is that the tender team did not have the relevant information, and that they lack technical expertise to communicate questions and information with technical departments. We recommend looking closer into this in further work in the company.

Discussion

Workshop findings. Much of what we identified during the root cause analysis workshop is incidents or high-level root causes. We were looking for incidents and root causes to cost and schedule overruns, and may have been blinded by this, as we did not look for the underlying reasons to what we discovered. It could have been beneficial to use the 5 why model more extensively than we did in our work. The root cause analysis revealed causes that may be the reason TQPs incur cost and schedule delays in projects, but not causes to why the number of TQPs increase during a project.

We have had unformal interviews/conversations with senior managers throughout our research. When they are confronted with our findings from the root cause analysis, they all agree with our results that qualification of products in parallel with projects causes problems. Our review of the reference project shows this as well.

Project-specific findings. Our research shows that the number of technology gaps and associated costs have grown during the reference project's execution phase. Reviews of project documents reveal that many TQPs are discovered well into the project execution phase. However, we do not have enough evidence to verify if the additional qualification programs in the project were caused by undiscovered technology gaps in the tendering phase or design changes during the project execution phase. The research by Tranoy and Muller (2014) showed that design changes in the project execution phase are normal and that these changes incur cost and possibly schedule delays. Late design changes may therefore contribute to some of the TQPs in the reference project.

The specific example we give of a component that has gone through multiple iterations of manufacturing due to material issues and strength has incurred serious cost overruns to the reference project. What started out as an undiscovered TQP in the bid, turned out to be a big cause of cost increase to the project. A chain of events seems to have caused this qualification program to be so unsuccessful. Firstly, the tender team did not identify the need for this particular TQP. If the tender team had identified this, the qualification program could have started much earlier than in the current situation. Next, the decision about changing material properties was an unsuccessful move. As the lead engineer explained, they had to take a fast decision based on the information they had. The project was already under time pressure when they realized they did not make the 20 M&B target as initially agreed between company and customer. The technical responsible knew that there was a chance that the new material properties could cause trouble, but with the information they had they deemed the risk acceptable. Unfortunately, the problems occurred. Based on the above example, we can conclude that the undiscovered or arisen technology gaps have incurred cost in the reference project, and that they may have caused schedule delays.

Collaboration. Through our research, we have had conversations with numerous employees from different departments. These conversations indicate that a major reason for the undiscovered qualification programs could be poor communication in the organization, that is, between the tender team and the discipline engineers. The tender team often lacks the specific technical competency that each of the discipline engineers have within their respective domains, as well as the discipline engineers often neglect the business point of view. Our observations indicate the need for a better collaboration between the tender team and the discipline engineers in order to improve the technical competence within the tender team, and thereby identify required TQPs in an earlier phase.

MBSE as the next step? The company could benefit from introducing a method for exchanging product information within the company, and for accessing this information when needed. Specifically, giving the tender teams easier access to product and systems information would be of great help. This could work if the company understand its significance. It is highly likely that the company will need access to SME knowledge to do that.

Our example, showing a qualification program not identified in the bid, became a significant cost escalator. Recall that the system was qualified for 10 M&B, but the customer required 40 M&B. If this information was readily available, for instance through a MBSE type of "tool", the tender team most probably would have discovered the technology gaps and induced a technology qualification program. Theories and cases from other industries display MBSE as a useful set of tools for our case, but it remains to be shown whether implementation of such a tool brings all these benefits to the company.

Credibility of data and limitations of the research. In our research, we have used the experience and knowledge of senior personnel, and information from one project as input to our research. These people have accumulated many years of experience by working in the oil and gas industry. Nevertheless, their input to our research is based on gut feeling and experience, and may therefore not be the absolute truth. However, our findings in the reference project correlate well with the experts' experience and gut feeling. Therefore, we have a good reason to believe that their input is credible in this case. However, we lack sufficient data to generalize further.

Application of tools and methodologies in our research. In this project, we applied quality management tools from the disciplines of Total Quality Management. These are described in the SE body of knowledge (BKCASE 2016 and INCOSE 2015), and were used to identify drivers for cost overruns through our research. We have conducted a root cause analysis by having a workshop with experts in the subsea oil and gas domain. The workshop was a good tool to facilitate discussion and brainstorming. We experienced that it was easier to capture incidents rather than actual root causes. It seems like people are more familiar and concerned with incidents, and do not know all the underlying causes to an incident.

We applied fishbone diagrams to capture the incidents and causes identified through the workshop. Unfortunately, we were not able to present the fishbone diagram in this paper due to confidentiality issues. The fishbone diagram gave a good overview of all the incidents and causes we captured in the workshop. Our experience is that it was a good communication tool to brainstorm. We also used the fishbone diagram to document the workshop for later use. This has allowed us to easily go back to find the captured information.

We divided the root causes into tangible groups. This division into problem areas influenced the top three list of most important root causes. If the division was more in terms of “valves, structures, etc.”, the result may have come out differently.

After the workshop, we applied the Matrix diagram and Pareto chart to sort causes and incidents in terms of their impact on cost and schedule overruns. Matrix diagram and Pareto chart were valuable in this context. The Matrix diagram was an easy-to-use tool that gave fast results in terms of causes and incidents criticality. The Pareto chart was a good tool to visualize the results from the Matrix diagram.

The application of a workshop, fishbone diagram, Matrix diagram, and Pareto chart has been helpful in identifying causes of schedule and cost overruns. The tools have been useful in order to pinpoint the main causes. However, to dig deeper into the real causes, we had to interview personnel in different part of the company. These conversations have given a better perspective of the context of our research. The approach of asking the “why” question has been valuable in order to obtain the real causes to the problem, and future work will benefit from going even deeper in to the 5 why questions.

Conclusion

The oil and gas industry is continuously striving to cut costs and eliminate schedule slips. The researchers' cause and impact analysis shows that in the case under study, one of the major drivers for cost and schedule overruns is the technology qualification programs (TQP). The TQPs are run in parallel to the delivery projects. We investigated an ongoing project (reference project) in the organization, and found that the number of identified qualification programs increased dramatically throughout the project. For the reference project, it is shown that the organization fails to identify more than half of the TQPs in the bid phase. This caused cost escalation and possibly schedule slips in the reference project. Our research indicates that the communication between the tender team and the discipline engineers is poor, and affects the level of technical expertise and product knowledge within the tender team. As a result, the project identifies new technology gaps in the project execution phase. We found that an early identification of technology gaps in our reference project, could potentially have spared 69 % of the TQP cost. If this cost escalation can be avoided in future projects, it will reduce the overall cost of subsea production systems, and potentially increase the profitability of oil and gas field developments.

This work does not conclude whether unforeseen qualification programs impact the project execution schedule. Although our findings are unambiguous within the company and the reference project, we cannot extend this to a generic setting without further research. SPS suppliers and oil and gas companies would benefit from research on how schedule slips and cost overruns impact production start and total investment cost of offshore oil and gas projects in general. If research can pinpoint the biggest drivers, it is easier to tackle them and reduce the risk of them occurring.

References

- Andersen, B. and Fagerhaug T. N. 2006. “*Root Cause Analysis: Simplified Tools and Techniques.*” 2nd ed., American Society for Quality, Quality Press, Milwaukee.
- BKCASE Editorial Board. 2016. The Guide to the Systems Engineering Body of Knowledge (SEBoK), v. 1.7. R.D. Adcock (EIC). Hoboken, NJ: The Trustees of the Stevens Institute of Technology. Accessed November 2016. www.sebokwiki.org. BKCASE is managed and maintained by the Stevens Institute of Technology Systems Engineering Research Center, the International Council on Systems Engineering, and the Institute of Electrical and Electronics Engineers Computer Society.
- Bonaccorsi, A. and Lippardini, A. 1994. “Strategic Partnership in New Product Development: An Italian Case Study,” *Journal of Product Innovation Management*, vol. 11, no. 2, pp. 134-145.
- Croom, S. R. 2001. “The Dyadic Capabilities Concept: Examining the Processes of Key Supplier Involvement in Collaborative Product development,” *European Journal of Purchasing & Supply Management*, vol. 7, no. 1, pp. 29-37.
- DNV (Det Norske Veritas). 2011. DNV-RP-A203. Recommended Practice: Qualification of New Technology, JULY 2011. Oslo, NO.
- EY. 2014. “Spotlight on oil and gas megaprojects,” White paper by EY’s Global Oil & Gas Center. CSG No. 1407-1280223. <http://www.ey.com>.
- INCOSE (2015). *Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities* (4th ed), Walden, D. D., Roedler, G. J., Forsberg, K. J., Hameling, R. D., and Shortell, T. M. (Eds.). Dan Diego, CA: International Council of Systems Engineering Published by John Wiley & Sons, Inc.
- Ishikawa, Kaoru (1985), “What Is Total Quality Control? The Japanese Way (1 ed.)”, Englewood Cliffs, New Jersey: Prentice-Hall.
- Johnsen, T. E. 2009. “Supplier Involvement in New Product Development and Innovation: Tacking Stock and Looking to the Future,” *Journal of Purchasing & Supply Management*, vol. 15, no. 3, pp. 187-197.
- Korfiatis, P., Teresa, Z. D. and Blackburn, D. M. 2012. “Graphical CONOPS Development to Enhance Model Based Systems Engineering,” in *Industrial and Systems Engineering Research Conference*, Orlando, Florida, US, May 19-23.
- Marrow, E.W. 2012. “Oil and Gas Industry Megaprojects: Our Recent Track Record,” *Oil and Gas Facilities*, vol. 1, no. 2, April.
- Mehta, M. B. 2014. “Weighting for Success,” *Industrial Engineer*, vol. 46, no. 4, pp. 45-49.
- Nellore, R. and Balachandra, R. 2001. “Factors Influencing Success in Integrated Product Development (IPD) Projects,” *IEEE Transactions on Engineering Management*, vol. 48, no. 2, pp. 164-174.
- NPD (Norwegian Petroleum Directorate). 2013, “Evaluation of projects implemented on the Norwegian shelf.” White paper. <http://www.npd.no>.
- 2016. “The shelf in 2015 – Petroleum production.” 14 January. News from NPD 14.01.2016. <http://www.npd.no/en/news/News/2016/Summary/Petroleum-production/>.
- OED (Olje og Energidepartementet). 1999, “Analyse av investeringsutviklingen på kontinentalsokkelen.” (Analysis of the investment development on the continental shelf by the Norwegian Ministry of Petroleum and Energy.) NOU1999:11.
- Offshore.no. 2011 (1). “The reason for cost overruns on the Norwegian continental shelf,” Publisert Published 25.01.2011 08:11. http://offshore.no/sak/31641_derfor_sprekker_utbyggingene.
- 2011 (2). “10 projects with a total cost overrun of 96 B.NOK.” Published 19.01.2011. http://offshore.no/sak/31592_til_sprekker_til_96_milliarder.
- Oil & Gas UK. 2015. “Activity Survey 2015.” White paper published by the UK Oil and Gas Industry Association Limited. ISBN 1 903 004 39 X.
- Petro Global News. 2014. “Dong Energy: Two North Sea projects delayed.” Published 14 August 2014. <http://petroglobalnews.com/2014/08/dong-energy-two-north-sea-projects-delayed/>.

- Scandinavian Oil Gas Magazine 2015. “Inpex to delay production start for Ichthys LNG.” Published 14 September 2015. <http://www.scandoil.com/moxie-bm2/news/inpex-to-delay-production-start-for-ichthys-lng.shtml>.
- Topper, S. J. and Horner, N. C. 2013. “Model-Based Systems Engineering in Support of Complex Systems Development.” *The Johns Hopkins APL Technical Digest*, vol. 32, no. 1, pp. 419-432.
- Tranøy, E. and Muller, G. 2012. “Reduction of Late Design Changes Trough Early Phase Need Analysis.” INCOSE Conference, Las Vegas, US.
- Wall Street J. (The Wall Street Journal). 2016. “Eni’s Arctic Oil Field Approved After Delays and Overruns.” Published 19 January 2016. <http://www.wsj.com/articles/enis-arctic-oil-field-approved-after-delays-and-overruns-1453239868>.
- Wu, J. and Wu. Z. 2015. “Key supplier relationships and product introduction success: The moderating roles of self-enforcement and interdependence between buyer and supplier.” *Industrial Marketing Management*, vol. 46, pp. 183-192.

Biography

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