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Evolving tolerance management for increased robustness of subsea installation operations

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Abstract. Low oil prices leads to a need for large cost reductions and improved effectiveness in the subsea oil and gas industry. At the same time, production in harsher environment and deeper water is inducing a need for more complex production systems. Increasing complexity reduces the tolerances for successful manufacturing and installation. Increasing robustness of the installation process can reduce installation costs. Robustness of the installation process is dependent on successful tolerance management. This paper investigates different methods for tolerance management. The conclusion is that successful tolerance management partly is independent on the chosen method for tolerance analysis. The research shows that successful tolerance management relies on understanding of the tolerance chain, cooperation, and early initiation. We applied system modelling as a system engineering approach to support manually calculated tolerance budgets. The research finds that this supports understanding, exploration, and communication. We recommend this as best practice. The research shows that tolerance management can contribute to increased robustness of the installation process by including manufacturing and operational factors in the tolerance analysis. System modelling and budgeting support discussion and exploration of these factors.

Introduction

Domain. This paper focuses on the subsea oil and gas domain, and Subsea Production Systems (SPS). The industry seeks technology to enable production in deeper water and harsher environment. This increases the complexity of the production system and its installation. Increasing complexity decreases the margins for successful fabrication and installation of the SPS, consequently increasing the requirements for engineering and design. Harsher environment increases the requirements of materials in the SPS, increasing the hardware costs. Simultaneously, the industry faces challenges of low oil prices. As of January 2016, some of the world's largest oil and gas companies had shelved investments in new oil and gas projects worth of 400 million USD (Adams 2016). Globally, the industry was facing 258000 layoffs of oil and gas workers as of December 2015 (Borney 2016). This induces the need for reducing costs and improving effectiveness in all stages of the production. Cost reductions are however in conflict with the need for more complex production systems. A solution to this conflict demands a holistic and systematic approach, where operators and contractors need to consider issues outside their area of responsibility. We research how SPS contractors can contribute to reduce costs despite the increasing complexity of the production systems.

Company of research. The company being target for this research is a Norwegian based supplier of products and services to the oil and gas industry. The company consists of several business areas. The business area that delivers SPSs is target for this research. This business area supplies Engineering, Procurement & Construction (EPC) in the subsea oil and gas domain.

Problem. The competition to win contracts for supplying SPSs is intense. Costs are a determining factor in these competitions. The installation process contributes substantially to the total project costs of a SPS development. Installation time and vessel/rig rental determine the installation costs. Rental cost of installation rigs can be up to 8 million NOK per day. Installation of one single Xmas Tree (XT) can vary in length from two to four weeks. Consequently, installation of one single XT can cost between 112 and 224 million NOK. According to engineers, the typical price of a XT is 40 million NOK. We see that reduction of installation costs can contribute to a significant decrease of the break-even rate. An aspect of the installation cost is the robustness of the installation operations. Reduced margins for successful manufacturing and installation challenge the robustness of the installation process. This results in increased installation costs. Improved robustness of the installation process depends on successful tolerance management. The company faces challenges with inconsistency of tolerance analysis methods.

Goal. The company needs to increase competitiveness. Reducing costs is a prerequisite for increased competitiveness in this setting. Ensuring robustness of installation would save the company's clients installation costs, and consequently improve the company's competitiveness towards competing contractors. To achieve a robust installation process, we want to minimize sensitivity towards external noise, causing failure and delay. Failures or delays cause the operators additional installation costs, and we want to reduce these costs.

The goal of this research is evolving tolerance management to support increased robustness of the installation process.

Solution - SE application. We use system modelling and budgeting as tools to manage tolerances. System modeling is a core SE technique and focuses on visualizing different views of the system of interest. This approach facilitates exploration, discussion, validation, and training, which all generate understanding of the system of interest. System modeling and simulation used during architecture and design can reduce the risk of system failure (INCOSE 2015).

Research questions. We ask the following research questions:
- How can current tolerance analysis methods evolve to improve tolerance management?
- What factors impact the tolerance management approach?
- How can tolerance management support robustness of installation?

To answer these questions, we research previous and current methods for tolerance management in the company. We investigate tolerance issues occurred in previous projects and the reason for the occurrence. By using tolerance budgets and system modelling for tolerance management in a study for a SPS, we validate this method. We interview clients of the company to identify their needs in deployment of a SPS.

Subsea context

Subsea oil and gas project costs. Operators of oil and gas production determine the commercial robustness of a production project by calculating a break-even rate. The break-even rate is the breaking point where the up-front investments (CAPEX) and operating costs (OPEX) are in balance with the income from the production. Consequently, the break-even rate is a metric for the lowest price needed per sold unit for commercial successfulness of a project. The commercial successfulness is dependent on the oil price, and the production volume. There is uncertainty associated with break-even rate and commercial successfulness. The oil price floats, and even though operators make an estimate over OPEX throughout the project life cycle, the exact maintenance and workover cost is unknown. Operators continuously strive to reduce the break-even rate. Operators consider the costs of installation of a SPS as part of CAPEX.

Subsea Production System. Figure 1 shows a typical SPS. The production unit, known as a Xmas tree (XT), is a package of valves that controls the flow of hydrocarbons. Templates are structures with several XT slots and a manifold in the middle, enabling cluster placement of XTs. Satellite guide bases enable installation of XTs on stand-alone wells. Production jumpers connect the satellite XTs to a manifold for gathering of production flow. The flow is further transported topside to a Floating Production, Storage and Offloading vessel (FPSO), an oil platform or other tieback solutions. In the company researched, different product groups, called work packs (WPs), produce the different components in a SPS system.

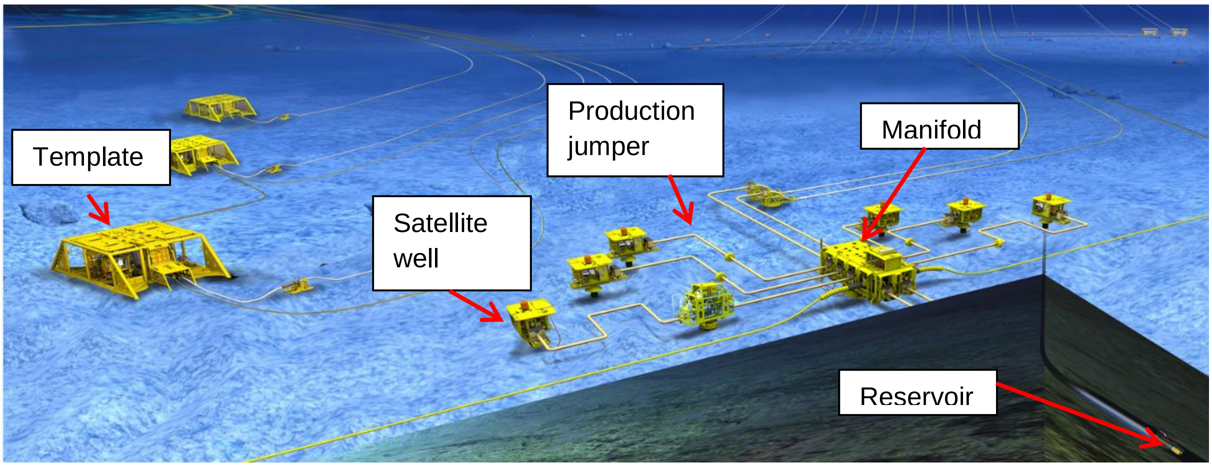


Figure 1. Field layout with template and satellite structures

Manufacturing and installation of a SPS. When installing the components in a SPS, there must be some clearance between the components for the installation to be possible. There are tolerances in both manufacturing and installation of the SPS. We define installation tolerances as an envelope for successful and safe installation; this refers to how much two components can be misaligned and still be able to install successfully. We define manufacturing tolerances as the maximum deviation a component characteristic can have from the nominal design value without losing functionality as part of the SPS. The manufacturing tolerances, the clearances between the components and the needed envelope for successful and safe installation all together form a tolerance chain that will affect the success of the final installation. Engineers assess and analyze the tolerance chain through complex calculation operations. We define engineering, design, assessment, and analysis of the tolerance chain as tolerance management.

Robustness of the installation process. Factors such as seabed conditions, sea depth, sea currents and weather affect the degree of difficulty and time spent on the installation operation. Sea depth determines the time spent on lowering tools and equipment down to the seabed. The sea depth is also affecting the weight of the installation wires and landing strings, causing additional stress factors such as torsion. Seabed conditions refer to incline of seabed and seabed materials. Muddy seabed conditions compromises visibility, increasing the time spent on the installation operation. Sea currents can cause tools and equipment to drift during installation, making the installation operation difficult. The same applies for weather conditions. These factors affect the robustness of the installation process. ANSI and IEEE defines in “Standard Glossary of Software Engineering Terminology” robustness as “the degree to which a system or component can function correctly in the presence of invalid inputs or stressful environmental conditions” (IEEE 1990). Stressful environmental conditions are noise factors that may cause failure or delay of the installation process. There are two main categories for noise factors; Internal and external. The external noise factors refer to factors that are uncontrollable, such as sea state, swell and current. Internal noise relates to controllable factors, such as wear of products and manufacturing errors. In this setting, we define robustness as the ability to perform the installation operation correctly the first time, within project specific cost and time limits.

Subsea installation

XT Configurations. There are two main configurations of the XTs: the horizontal XT (HXT) and the vertical XT (VXT); see Figure 2.

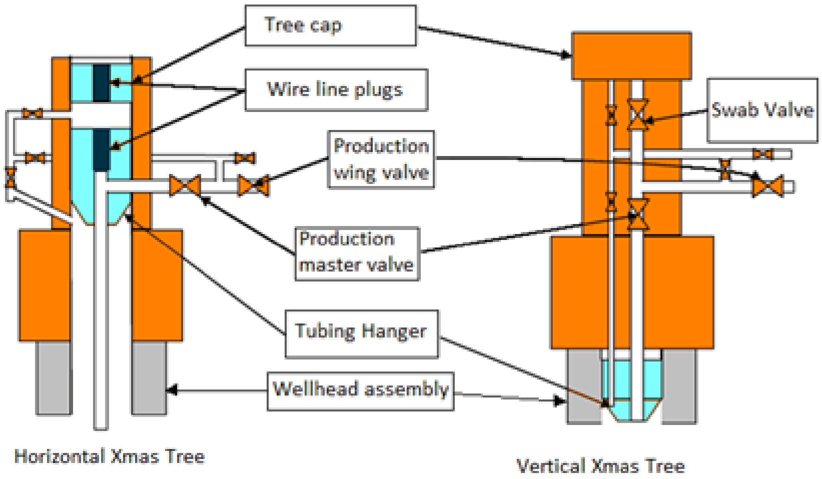


Figure 2. Horizontal and vertical Xmas tree

The Tubing Hanger (TH) holds the tubing going into the reservoir. The TH is installed in the HXT after the HXT has been installed. For the VXT it is installed in the wellhead prior to installation of the VXT. The VXT configuration enables retrieval of the VXT without retrieving the TH, which enables easier work over and maintenance operations. A template system requires alignment and orientation of the XT towards the tie-in hub on the manifold. The tie-in hub on the manifold is a fixed structure with no possibilities for adjustment. The VXTs require alignment towards the TH in addition. This means that the VXT aligns towards two separate components being in separate planes. We define this envelope for alignment with six degrees of freedom. This refers to the possible rotational misalignment of VXT; see Figure 3. Operators have until the recent years most commonly used the HXT configuration. Today, the VXTs are more common. The complexity of the tolerance chain has increased due to turnover from HXTs to VXTs.

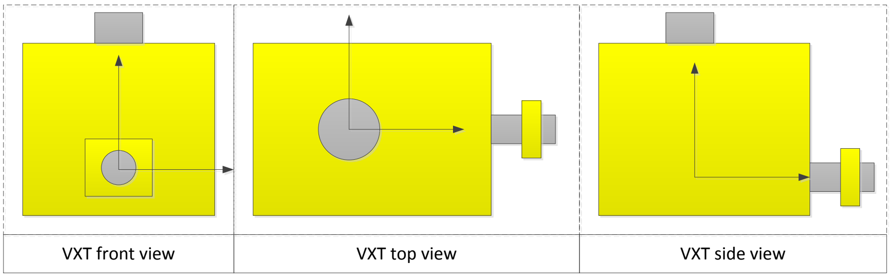


Figure 3. Rotational alignment of the VXT, relative to the well axis

Critical areas in the tolerance chain. Figure 4 shows a simple explanation of the sequences in the installation. The figure deviates between operations for specific types of subsea systems, and common operations, such as the landing of the Blow-Out Preventer (BOP).

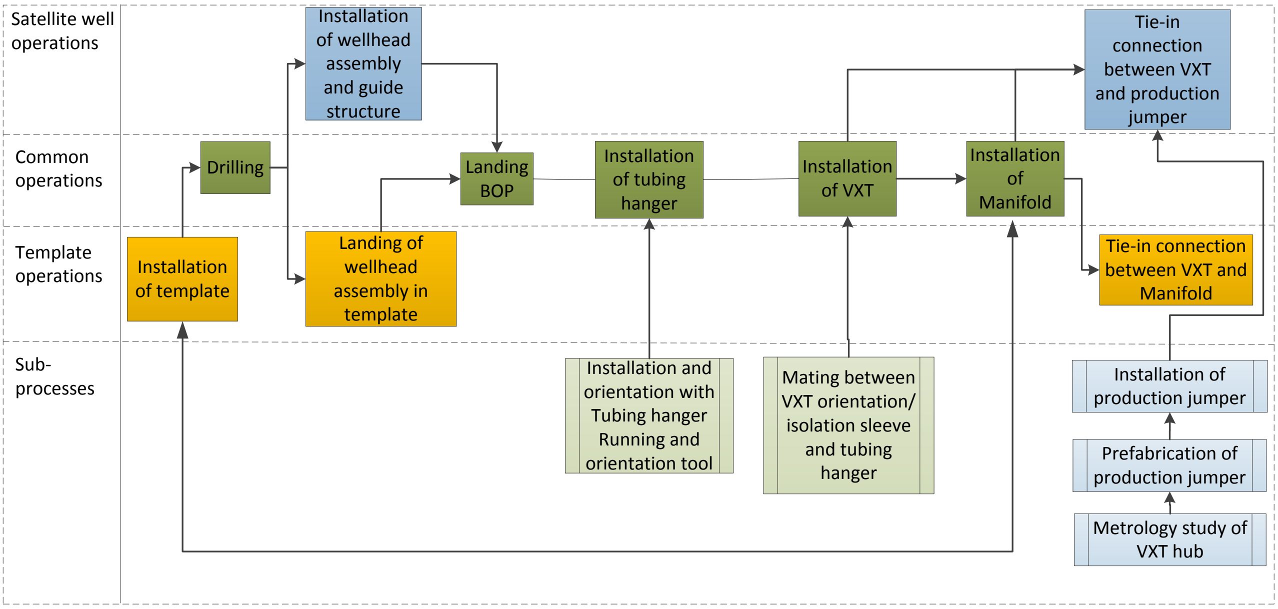


Figure 4. Flowchart of operations in the installation sequence

Operators monitor production using down-hole sensors. Hydraulic and electric lines to these sensors run through the XT sleeve and further through the TH. This is where the TH interfaces the VXT. The critical part of this interface is the mating between the hydraulic connectors, the production bore, and the annulus bore. The most critical alignment is in the Rz-direction, meaning that rotational alignment is determining successful mating. These interfaces require an exact and correct mating for successful installation. This makes the orientation of the TH a critical factor for the orientation of the VXT. The tie-in hub on the VXT interfaces the tie-in hub on the manifold if in a template, or the termination head of a production jumper if on a satellite well.

Research method

We performed this research with a combination of industry-as-laboratory (Muller 2013), and action based research (Muller 2013). Parts of the research target methods for tolerance management used by the company, and we evaluate the methods. The basis for this evaluation is a combination of qualitative interviews with key personnel involved in conducting the methods, and research of the results of the methods. The interview objects are company engineers, holding system engineering and product engineering positions in the projects researched. As part of the research, we also used a third method for tolerance management in an ongoing project. Qualitative interviews with product engineers involved are basis for the evaluation of this method. We evaluate the methods for the following aspects:

- Credibility amongst engineers applying the methods
- Reliability

To ensure that we also have the clients in focus, we use qualitative interviews of company clients as basis for identification of their needs in deploying a SPS. The interview objects are system engineers representing their respective company. We acknowledge that the interviewed engineers do not necessarily represent the opinion of their company, but their own views and perspectives.

The numbers we show in this research are illustrative; for confidentiality, the values have been adapted slightly.

Current way of working with tolerance management in the company

Handling of tolerances. The concept of installation tolerances is a top-down approach – this concept focuses on systems and the interaction between components. Engineers strive for having as large installation tolerances as possible to maximize robustness of the installation process. The concept of machining and fabrication tolerance is a bottom-up approach – machining and fabrication tolerances are the margins of how much products can differ from the target, or drawing specifications without loss of functionality. While engineers strive for allowing as large fabrication tolerances as possible, they strive for having as little deviation from nominal as possible. Company WPs are responsible for handling the machining and fabrication tolerances of their own products. The installation tolerances and tolerance chain are different, as managing of this requires cooperation between the WPs and external stakeholders.

Company project execution diagram. The company has a diagram for standard execution of projects. This diagram links and details all activities in project execution, and ensures predictability. A project consists of several phases, starting with the feasibility and concept phase and ending with commissioning; see Figure 5.

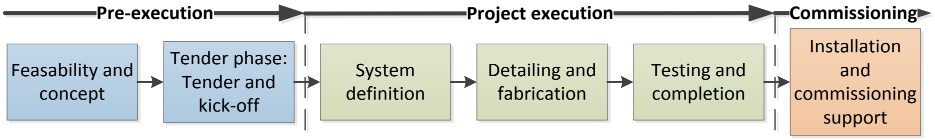


Figure 5. Stages in the company project execution diagram

There are no procedures or specifications in the project execution diagram for management of the tolerance chain. This does not imply that the company has not conducted tolerance management in previous projects, but this implies two things:

Tolerance management is conducted internally by the work packages as part of design

How to conduct tolerance management is up to each project to decide

Not having a standardized method for conducting tolerance management leads to less predictability and more uncertainty on this topic. Conduction by work packages leads to larger risks for tolerance issues as a multidisciplinary approach may be lacking. The result of the tolerance management is consequently dependent on the choices made and actions performed by the engineers involved in the process.

Discovery of issues and Non Conformance Reports. Company engineers discover issues during manufacturing and while testing the produced equipment. There are several stages of testing, and the final stage of testing before hand-over to client is System Integration Testing (SIT). The purpose of SIT is to assemble smaller parts of the production system and test functionality and mechanical interfaces. Another purpose of SIT is to test offshore procedures for installation, operation, and retrieval of system components. SIT is the most critical testing stage to discover issues that requires design changes. At this stage, changes are costly, and can induce delays of delivery. However, engineers cannot fully validate tolerance management until this stage, and while installing the equipment subsea. The company has a system for recording issues discovered during manufacturing, fabrication and testing of equipment. When engineers discover issues, they report this as a Non Conformance Report (NCR). The NCR includes reason for NCR, why, how and when the engineers discovered the issue, and the responsible owner of the issue. The responsible owner then has to manage the issue and is responsible for closing the NCR.

Engineers may also solve issues without reporting NCRs. Issues occurring during installation is not part of company scope of work. Company engineers are hence not reporting these in the NCR system. The consequence is that not all issues occurring are traceable in the NCR system. Hence is the NCRs alone not a perfectly suited measure of the effectiveness of a tolerance management method in the perspective of robustness of installation.

Tolerance management in the company. The company has identified that currently the process of tolerance management is inconsistent regarding methodology and results. Inconsistency is constraining development of the tolerance management process. Further, it complicates transfer of experience between projects. The company wishes to standardize this process to ensure consistency. Previous research developed a method for tolerance management using tolerance budgets and system modeling (Henanger 2015). This method needs further validation. Two other methods have previously been in use for tolerance management by the company. One of these methods involves dedicated software. The other utilizes manual calculations. We study if any of these methods is preferred to the other. A decisive factor for such preference is the credibility and reliability of the methods. The purpose of this study is to recommend a standardized method for tolerance management in the company.

The client's needs

We have interviewed three clients about their needs in deploying a SPS. Clients identify installation cost as an important factor of a SPS project. The strategies to achieve low installation costs are dependent on the client and the project. We identify the following needs:

- Low weight and volume of system components
- Flexibility in installation
- Independency from specialty tools

Independency from specialty tools reduces hardware costs and the need for special competence of such tools. Specialty tools in this setting means tooling having one purpose for functionality, and/or being specifically adapted for a project. Independency enables re-use of tools from project to project.

Flexibility in installation reduces the installation time. A flexible order of operations enables operators to perform installation based on availability of the components and weather conditions. The client addressing flexibility as a need argues that product standardization will mitigate increasing complexity of the SPS as consequence of increased flexibility. They argue that they earn additional cost of standardization back by the reduced lead-time for products.

Size and weight of the system components determine the lifting capacity and size requirements for the installation rig or vessel. The rental costs increase with the size of the vessel, rigs being the most costly.

Tolerance is a challenge to the company. Tolerance issues can lead to delays in the delivery and errors during installation. They can cause severe commercial consequences to clients. Hence, the clients are expecting on-time deliveries, and no tolerance related errors during installation.

Tolerance management in practice

Research basis. We use three company projects as basis for this research. We hereby refer to these projects as project A, B and C.

We research various methods for tolerance management. Project teams performed tolerance management differently in project A and B. We conduct a comparative research of the methods they used, focusing on credibility and reliability of the methods. First, we study tolerance issues reported for these projects. The numbers of tolerance issues reported indicates the reliability of the methods. Secondly, we interview key personnel involved about the methods' credibility. In addition, we research the time spent on the methods. By comparing the time spent on each method with the result of the method, this can imply the efficiency of the method.

Tolerance management in project A. Project A is located on the coast of Congo. The project consists of 18 satellite production wells, 10 satellite water injection wells, and 6 manifolds. The sea depth is approximately 1350m. The operator of the project is a large international oil company.

Project A used a software tool (RD&T 2016) for tolerance management currently in use in the car industry, being new to the company. The software utilizes the Geometrical Dimensioning & Tolerancing (GD&T) method for input. GD&T is a symbolic language for manufacturing drawings that defines and communicates the allowed deviation of the location, dimension, orientation, size and form of each feature of a design model. This enables an accurate calculation of the tolerance chain in 3D. Additionally, this creates a direct link between the tolerance analysis and manufacturing. The software utilizes a statistical model for calculation of the tolerance chain. This statistical model uses given tolerance criteria and utilizes a ten-sigma Monte Carlo simulation with a uniform probability distribution. The software treats the mean value of the simulation as the statistically most probable tolerance value. Engineers that applied the software state that the outcome of the model is hard to predict. In the worst case, the actual manufactured component may end up outside the bounds of predicted tolerance values.

Result of tolerance management in project A. An estimate shows that the hours spent on this activity is approximately 3500 hours. The total amount of hours booked on this project is approximately 2358600. This means that this activity makes up 0.13 % of the total. We study NCRs reported in project A and find 57 NCRs that relate to tolerance issues. However, this number is inaccurate due to variation in descriptions of NCRs and difficulties in sorting out NCRs that relates to tolerances. As engineers may solve issues without reporting NCRs, there may be more issues than the NCR system shows.

Credibility of tolerance management in project A. Engineers involved in project A are not conclusive about the method used. The GD&T method makes the creation of the input to the method time consuming. Engineers point out in the evaluation of the method that both understanding of the software and understanding of tolerances are key factors for successful conduction. Engineers involved in this also point out that not being in control over every operation within the software makes validation of the result difficult. This decreases the value of the accurate result.

Installation issues in project A. Through interviews with engineers that participated in the installation sequence in project A, we learn that project A experienced some installation issues. These issues relate to installation of the THs. When installing a SPS, operators use a Blow-Out Preventer (BOP) as a tool for temporarily control the pressure in the well during installation and drilling. Down-whole equipment such as the TH is lowered through the BOP and into the well. Due to the sea depth and weight of the landing string, a torsion effect of the landing string occurred, consequently leading to the landing string being in a non-concentric position in the BOP. See Figure 6. The left most figure shows the landing string in nominal position, with the TH installation tools and the TH in the BOP. The rightmost picture shows the effect of torsion of the landing string, leading to a non-concentric position in the BOP. The consequence of the landing string being in a non-concentric position is failure of installation of the TH. In project A, this led to repeated attempts before successful installation of the TH, consequently compromising the robustness of the installation operation.

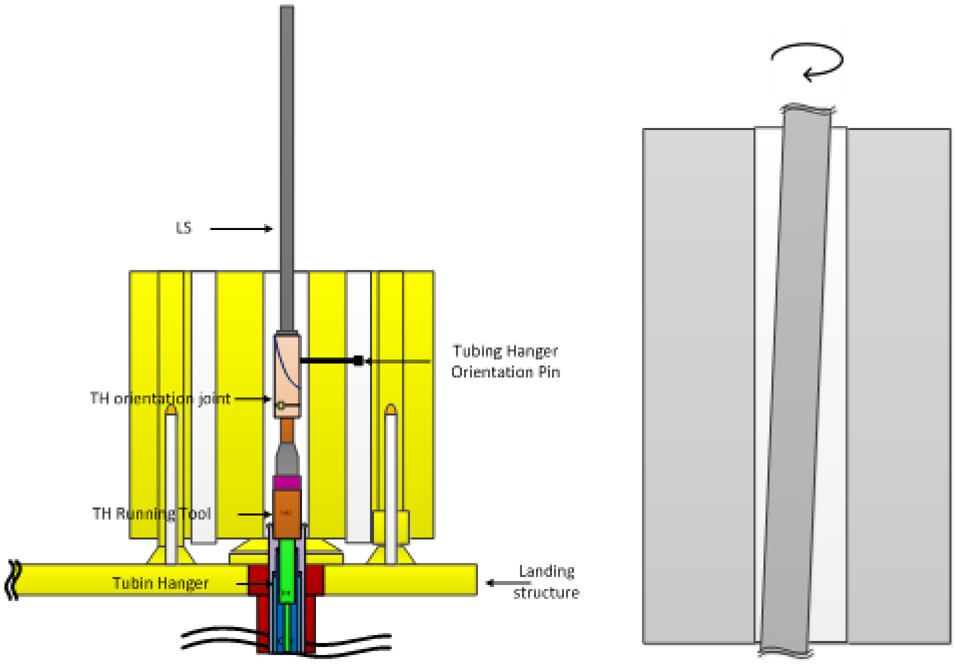


Figure 6. Torsion of landing string

Tolerance management in Project B. Project B is located on the coast of Angola. This project consists of 36 satellite production wells, 29 satellite water injection wells, and 20 manifolds. The sea depth is between 1500 and 2000m. The operator is the same as for project A.

Project B uses manually calculated tolerance budgets. This model identifies the worst case of all tolerance criteria and calculates the summarized worst-case tolerance chain in 2D. The report of the tolerance analysis contains manufacturing drawings of the products included in the tolerance analysis. Input to the tolerance analysis is from these drawings. The outcome of this model is very predictable.

Result of tolerance management in project B. An estimate shows that the hours spent on tolerance management is approximately 2200 hours. The total amount of hours booked on this project is approximately 1789000. Tolerance management makes up 0.1% of this. We study NCRs reported in project B and find 158 NCRs that relate to tolerance issues.

Credibility of tolerance management in project B. The engineers involved in applying the method find it credible. However, the method used in project B still needs validation, due to the project being in progress. A drawback of the worst-case method is that it calculates a scenario that is not likely to happen. Designing for a worst-case scenario that is unlikely to occur, leads to unnecessary high costs.

Analysis of tolerance management in project A and B. Credibility and reliability are key factors for determining an appropriate method for tolerance management. Table 1 shows tolerance related NCRs, hours invested on the respective tolerance analysis and number of units produced, for both projects. The company classifies items with a material level. A component can e.g. be at material level 3. The parts within this component will then be at lower material levels. We obtained the numbers of units produced from the projects' Bill of Materials at the same material level. The two leftmost columns show calculations of units per NCR and units per NCR per hour.

Table 1. Effectiveness of tolerance methods

	Tolerance related NCRs	Hours invested on tolerance analysis	Hours invested in % of total hours spent on project	Units produced (at BOM level 3)	Units per NCR	Units per NCR per hour
Project A	57	3500	0,13%	6121	107,4	0,031
Project B	158	2200	0,10%	16454	104,1	0,047

Table 1 shows that the number of units per NCR is slightly higher for project A than B. This implies that project A had higher success rate of the production than project B. Dividing units per NCR on hours invested on the tolerance analysis, we get a value for the effectiveness of the tolerance analysis. We see that project B has a higher value than project A. This implies that tolerance analysis in project B was more effective than tolerance analysis in project A. The table shows that the differences of success rate and effectiveness are marginal.

Project A is concerned about the difficulty of conducting tolerance management iteratively with the method they used. This is due to lack of control over the internal processes of the tool, also making validation of the results difficult. However, engineers point out the direct link between this method and the actual manufacturing as an advantage. Project B did not use system modelling for support. A late start of the tolerance analysis caused a lack of cooperation between work packs during tolerance management. Engineers initiated the analysis after the production of the equipment had started. They did not carry out an iterative tolerance management process; they were only using manufacturing drawings for input. Engineers in project B identify this as an area for improvement of the method they conducted. Both engineers involved in project A and project B points out cooperation between the different work packs as a key factor for successful tolerance management.

Specific tolerance issues. Engineers involved in both project A and project B point out that manufacturing the production/annulus bores and hydraulic couplers in the TH, TH running tool and XT sleeve within their positional tolerances is a challenge. These positional tolerances have very small margins for acceptance. The consequence of deviations in these tolerances is critical. Critical in this setting means that deviations may result in malfunction. Both project A and project B had significant issues with these positional tolerances. Project A used a statistical (RMS) tolerance analysis method, while project B used a worst-case (RSS) method. Treating the positional tolerance with different methods and still facing the same issues implies that the method for analyzing these tolerances is insignificant for the success of fabrication. However, engineers involved suggest that a worst-case method is better suited, considering the consequence of deviations. All though, options are that neither of the above mentioned methods were implemented correctly, or/and that alternative methods could be more effective.

Evaluation performed by the involved engineers finds that errors in fabrication are the main source for the issues with positional tolerances. The errors are complex with several causes. One cause engineers identified is immaturity of the fabrication process. This immaturity is due to the turnover from HXT to VXT, still being new to the company. The fabrication team experienced that they improved during fabrication, as they learned from the errors occurring. This implies immaturity of the manufacturing process.

Considering these issues and the marginal differences of the results, we see in Table 1, we cannot conclude that the method for tolerance analysis is decisive for successful tolerance management.

Conduction of tolerance management in project C. Project C is a currently ongoing company SPS study. This project will be located on the Norwegian continental shelf in the Barents Sea. The operator of the project is a large Norwegian oil and gas company. The sea depth of the project is approximately

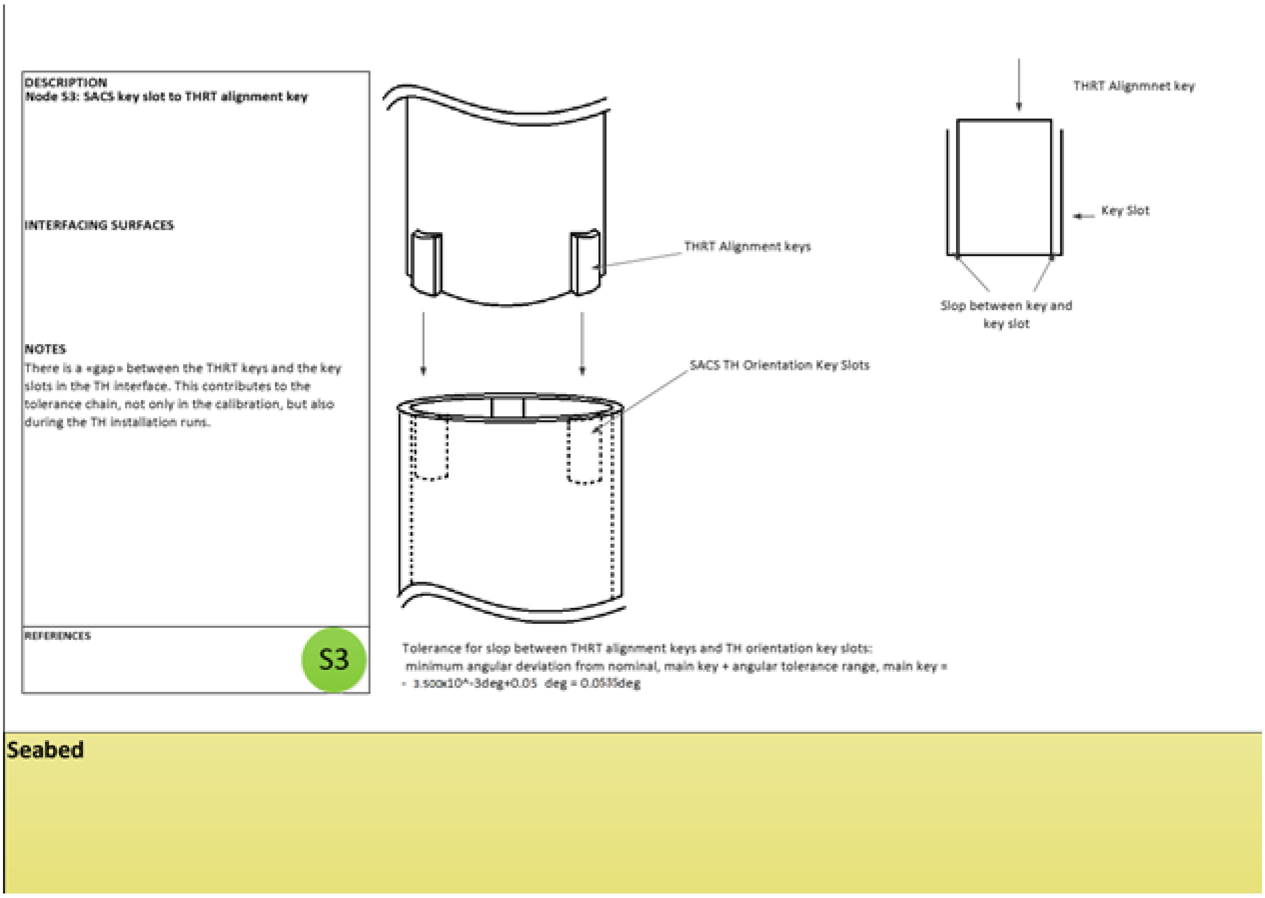
1250m. The operator wants to explore a combined solution with installation of VXTs in 4-slot templates and installation of VXTs on satellite Installation Guide Structures (IGS).

For tolerance management in project C, we used tolerance budgets supported by system modeling. The tolerance chain starts with drilling of the well, and ends when all parts of the SPS is installed and connected. Due to simplicity and company scope, the tolerance budget we used in this investigation summarizes the tolerance chain in installation of the Vertical XT (VXT), relative to the well axis. The tolerance budget considers manufacturing tolerances as well as installation tolerances. We used system modelling to support the tolerance budget by visualization.

During this research, we investigate the use of tolerance budgets and system modeling for successful tolerance management. We divided the tolerance budget into tolerance nodes, and modeled the nodes in the budget; see Figure 7 as an example. Tolerance management should be an iterative process: Work pack engineers supply input for tolerance values, system engineers calculate the tolerance chain, find areas of concern and give feedback to the WP engineers. WP engineers make adjustments and supply new input. We initiated tolerance management during early design phase to research if this enables an iterative adjustment process. We showed the models during design meetings with design engineers from all work packages present. An important part of the method is to enhance communication, and get the involved engineers to understand the tolerance chain and the dependencies of tolerances between components. Understanding and communication are prerequisites for cooperation. Understanding and cooperation are also important for achieving the overall goal of improving robustness and reducing costs. Another purpose of system modelling is to prevent loss of tacit knowledge, enabling future investigation of the tolerance budget by any engineer. The benefit of this is consistency in how the company performs tolerance management.

This method requires some additional work during the engineering phase of the projects. One engineer need to generate the budget, create the models and iteratively update this throughout the engineering phase. It is important to note that the input to the budget and the models shall come from the WPs.

We ask design engineers in project C how they consider the supporting models. They respond that the supporting models enhance understanding, and supports discussion and exploration. They also highlight that the models allow for future verification and modification by any engineer.



DESCRIPTION
Node S3: SACS key slot to THRT alignment key

INTERFACING SURFACES

NOTES
There is a «gap» between the THRT keys and the key slots in the TH interface. This contributes to the tolerance chain, not only in the calibration, but also during the TH installation runs.

REFERENCES

Tolerance for slop between THRT alignment keys and TH orientation key slots:
minimum angular deviation from nominal, main key + angular tolerance range, main key =
= 3.500x10^-3deg+0.05 deg = 0.0535deg

Figure 7. Example of a model of a tolerance node

We conducted tolerance management in the study phase of a project. To mitigate tolerance issues in the tie-in hub on the VXT and on the manifold/production jumper, engineers in project C decided to change from a horizontally connected to a vertically connected tie-in system. This reduces the misaligning effect of rotation of the XT. Except for engineers hours put into design of the system, this had no additional cost.

Project C learned from the installation process in project A that torsion of the landing string could cause issues. To mitigate such issues, we included the non-concentricity of the landing string in the tolerance chain. Through further exploration of this issue, design engineers came up with a solution to this problem; see Figure 8. The solution is a centralizer attached to the landing string that will keep the landing string in a concentric position in the BOP.

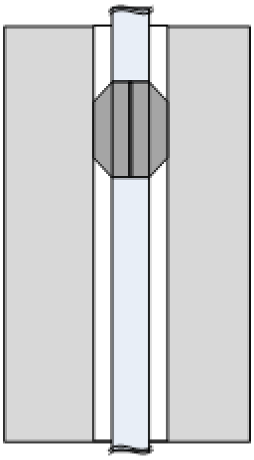


Figure 8. Centralizer to mitigate torsion effects

Method for tolerance management. Based on the evaluation of the tolerance management methods used in project A and B, and the findings in project C, we suggest a method for tolerance management. We find that the most appropriate method for performing tolerance management is using manually calculated tolerance budgets supported by modelling for visualization. We suggest using a combination of worst-case and statistical method. Engineers shall assess which of the two being the most appropriate for each respective part of the tolerance analysis. As the WPs are responsible for the tolerances of their own products, management of the tolerance chain is a multidisciplinary task, crossing boundaries of the WPs. Hence; Systems engineers should have the responsibility, and initiate tolerance management. However, the different work packs shall supply detailed tolerance calculations for each component. This can ensure cooperation between the WPs, highlighted by engineers in project A and B as a key factor for successful tolerance management. We suggest initiating tolerance management as early as possible, already in the concept and feasibility stage if applicable. Using tolerance budgets and system modelling requires some additional work during the engineering phase of a project. However, it is important to find the balance in the time spent creating the models and the complexity of the models. The purpose of these models is to enhance communication, understanding, and exploration. We show through project C that we achieve the enhancements using simple models, adapted to their specific intention.

Tolerance management and robustness of installation. We identified that reduction of installation costs reduces the break-even rate. Further, we identified that robustness of the installation process can contribute to reduction of the installation costs. Through interviews with clients, we learned that clients expect the installation process to be fully robust. Project A experienced issues in the installation sequence that compromised the robustness of the installation. As a mitigating action, project C accounted for this issue in the tolerance analysis. This shows that tolerance management can contribute to a robust installation process, consequently reducing installation costs and the break-even rate. Findings from only one project where the operator has not yet carried out the actual installation operation are the basis for this conclusion. Based on the observations, actions and interviews from project A and C, we propose the following focus areas to support a robust installation process:

Thorough tolerance management
  - Manufacturing contributions considered - Thorough tolerance management should consider tolerance contributions from manufacturing. This means that possible deviations from nominal due to manufacturing factors of both tools and equipment shall be included in the tolerance chain
  - Interfaces considered
  - Operational factors considered - Operational factors are such as torsion of the landing string, which could result in a non-centric position relative to the well.

Maturity of tools - Maturity of tools relates to the Technology Readiness Level (TRL) of the installation tool used

Maturity of operations - Maturity of operations considers the combined maturity of the tool used and the equipment installed for a specific operation. For instance, this could be installing newly developed equipment using field proven tools. A field proven tool is not necessarily ensuring maturity of the operation

By considering and mitigating such factors, tolerance management could support a robust installation operation, consequently supporting a reduction of the break-even rate. Another important factor is to learn from other projects. Ensuring proper knowledge transferring is critical for improvement and development of the tolerance management process. Project C used tolerance budgets and system modelling for tolerance management, and this supported exploration and discussion of both manufacturing and operational factors.

Conclusions

The goal of this research was to identify which factors impact the approach for tolerance management, with the purpose of evolving tolerance management to increase robustness of subsea installation operations, and increase the company's competitiveness. To achieve this, we have studied different methods for tolerance management. We asked the following research question: What factors impact the tolerance management approach? Through the study we conducted, we found that understanding of tolerance chain is a success criterion. The study shows that system modelling and budgeting enhances understanding and discussion. The study also showed that cooperation between the work packages is important. The tolerances between the interacting components are critical to achieve success during installation of an SPS. A factor impacting the approach for tolerance management is hence that the work packages develop understanding of each other's tolerances, and that culture for systematic thinking is developed. The research shows that system modelling and budgeting enabled an iterative design process. In the project where this method was used, the WPs cooperated to find design solutions to mitigate tolerance issues. Another factor impacting the approach for tolerance management is the necessary and available competence. Some approaches require special competence. The company should consider whether this is considered core competence or if this needs to be hired in. Considering understanding and cooperation, a key question is if that competence is transferable across projects and work packages. An example of this is project B, which used a method of tolerance analysis that partly relied on hired expertise, and very few key people. This led to limited understanding for tolerance analysis amongst other engineers involved in the project. We also saw that there are pros and cons of the approach for calculating the tolerance chain. Manual calculations are perceived to develop an understanding of tolerance chain, and is easy to adapt. Calculations in dedicated software is perceived as accurate, but is harder to adapt, and does not support understanding of the tolerance chain. Additionally, dedicated software is requiring special competence. The research we performed also showed that use of statistically calculated tolerances and tolerance calculations based on worst-case scenarios deviates minimally in impact of the tolerance management approach.

The industry seeks reduction of the break-even rate. Installation costs determine substantial shares of OPEX. We identified a potential for reducing the installation costs by increasing robustness of the installation process. We asked the research question: How can tolerance management support robustness of installation? Through the research, we learned that tolerance management could support a robust installation process by including manufacturing and operational factors in the tolerance analysis. A prerequisite for this is proper knowledge and experience sharing between projects. Tolerance budgets and system modelling supported exploration and discussion of manufacturing and operational factors.

Future Research

For future research, we suggest baselining and imbedding the integrated tolerance management process at enterprise level. The purpose of this is to control effective and efficient tolerance management and consequently SPS installation savings.

The research shows that tolerance issues occur partly due to immaturity of products and manufacturing processes. Maturity is a topic that could benefit for further investigation.

In this paper, we have focused on mitigating external noise factors. Future research could focus on internal noise factors by implementing the Taguchi methods for increasing robustness of the manufacturing process. We have not assessed quantity and time spent on tolerance issues outside the NCR system in this paper. This can be issues occurring in the installation process. We suggest that future research continue the investigation of robustness of the installation process by investigating time and quantity of tolerance issues outside the NCR system.

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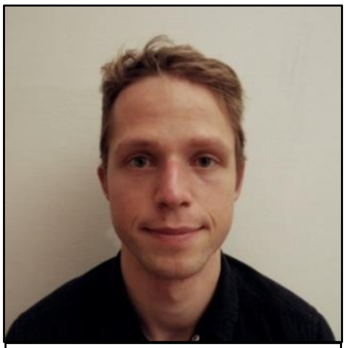
Biography



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Lars Petter Bryn works as a Systems Engineer in a Norwegian company suppling products and services to the oil and gas industry. He holds a Bachelor degree in energy and environmental engineering from Oslo University College from 2011. From 2011 until 2013, Lars Petter worked as a consultant engineer within building services, designing and dimensioning heating, water supply and ventilation in commercial and public buildings. He started to work as a system engineer in 2013 and has 3 years of experience as a systems engineer in the subsea oil and gas industry. Lars Petter has worked with several subsea production system projects and has experience with system integration testing and tolerance analysis of system components. This paper is the result of the research done for his M.Sc. in Systems Engineering at the University College of Southeast Norway.

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