UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF HYBRID PROBLEM SOLVING METHOD FOR SUBSEA INDUSTRY

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Thesis Submitted to the School of Graduate Studies Universiti Putra Malaysia, in Fulfilment of the Requirements for the Doctor of Philosophy

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July 2018

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Faculty : Engineering

This research is about the development of hybrid problem solving method to identify failures mainly applied in the subsea environment. A3 analysis with support from fishbone diagram and 5 whys analysis techniques were introduced to identify the actual cause of failures. The integration between these two techniques known as a hybrid problem solving method was then applied to identify the actual cause of failures. Upon identification of the actual cause of failure, improvement actions were taken to eliminate the actual cause. In this research, few comparisons in terms of different problem solving methodology applied for different industries namely aerospace, automotive, semi-conductor, chemical and oil and gas industry were reviewed and evaluated to understand the differences for closing the gaps with this new methodology. The proposed hybrid problem solving methodology was validated using a case study. The case study was focusing into the identification of the actual cause of failure related to the Inconel 718 fasteners that were used for Methanol Injection Tree Valve (MITV). Proposal on the lab analysis on fresh and failure fasteners was performed upon reviewing the outcome from the hybrid methodology to ensure the effectiveness of the analysis technique. Few analysis activities were performed consisting of mechanical property evaluation, chemical composition and microstructure review for validating the results. It was identified that the hardness value for Inconel 718 that was applied for this application was 18% higher than the maximum value of 40HRC as stated in MS-607 requirement of material Inconel 718 and API standard 6A718-2009. The data was then compared to understand the characteristics of the failure. One of the steps in the A3 technique is future state and target that requires a mitigation action to eliminate the cause of failure. This was performed by conducting a new material analysis e.g. L7M fasteners for future reference. There is no similar re-occurrence recorded upon implementing the mitigation actions of this problem solving methodology since 2012. This achievement can be concluded as a success of

identifying the real cause of failure using hybrid root cause analysis technique. Standard template for subsea's problem solving method was established upon completing the analysis for future use to increase efficiency and reduce cost of failures for each issue in the future.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN KAEDAH HIBRID BAGI PENYELESAIAN MASALAH DI DALAM INDUSTRI LAUTAN DALAM

Oleh

Ir. KHAIRUL NIZAM BIN MD TOHIT

Julai 2018

Pengerusi : Profesor Madya Norzima Binti Zulkifli, PhD
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Kajian ini adalah berkenaan pembangunan kaedah hibrid bagi penyelesaian masalah di dalam industri lautan dalam bagi mengesan punca kegagalan di dalam persekitaran industri lautan dalam. Analisis A3 yang mengguna pakai teknik punca dan kesan berserta 5 kenapa diperkenalkan bagi membantu mengesan punca kegagalan didalam aplikasi ini. Integrasi diantara teknik punca dan kesan bersama dengan 5 kenapa adalah dikenali sebagai teknik hibrid yang akan digunakan bagi mengenalpasti punca sebenar kegagalan. Sebaik punca sebenar dikenalpasti, tindakan pembaharuan telah diambil bagi menyingkirkan punca sebenar tersebut. Didalam kajian ini juga, beberapa perbandingan berkenaan teknik penyelesaian masalah yang digunapakai didalam industri yang berlainan seperti aeroangkasa, automotif, semi-konduktor, kimia dan minyak dan gas telah dianalisa bagi memahami konsep dan jurang bagi mengurangkan perbezaan tersebut bagi kegunaan pembangunan konsep hibrid. Cadangan pembangunan konsep hibrid ini telah diuji berserta dengan kajian kes sebenar. Kajian kes adalah cenderung menumpukan identifikasi punca kegagalan sebenar bagi aplikasi bolt Inkonel 718 pada Injap Kawalan Metanol (MITV) yang digunakan oleh industri lautan dalam. Cadangan analisis makmal pada bolt yang baru dan gagal telah dijalankan setelah meneliti keputusan analisis hibrid. Ini adalah untuk memastikan kebolehupayaan analisis hibrid ini untuk membantu menyelesaikan masalah di dalam industri lautan dalam. Beberapa analisis telah dilakukan seperti ujian bahan, ujian kimia dan ujian mikrostruktur bagi mengesahkan hipotesis yang digunapakai didalam melaksanakan kajian ini. Punca sebenar kegagalan bolt Inkonel 718 adalah berpunca daripada kekerasan bahan yang digunapakai adalah melebihi sebanyak 18% daripada kekerasan maksima bahan sebanyak 40 HRC seperti yang disyorkan oleh spesifikasi MS-607 dan standard API 6A 718-2009. Data yang telah dikumpulkan kemudiannya dibandingkan bagi memahami struktur dan sifat-sifat bahan. Salah satu tindakan di dalam analisa A3 ini adalah cadangan

untuk penambahbaikan bagi kegunaan pada masa hadapan. Ini telah dilakukan dengan melaksanakan ujian makmal terhadap bahan baru seperti bolt L7M bagi menggantikan bolt Inkonel 718 bagi kegunaan dan aplikasi yang sama. Tiada pengulangan insiden yang sama direkodkan sejak tahun 2012 semenjak pelaksanaan langkah-langkah pembetulan berdasarkan metodologi penyelesaian masalah hibrid ini dilaksanakan. Kejayaan ini adalah berpunca daripada pengenalan kaedah hibrid didalam mengenalpasti punca masalah sebenar yang dihadapi. Templat rasmi bagi kegunaan penyelesaian masalah di dalam lautan dalam telah diwujudkan bagi rujukan dan kegunaan pada masa hadapan bagi meningkatkan kecekapan dan mengurangkan kos kegagalan pada setiap masalah.

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Thank you very much.
Ir. Khairul Nizam Bin Md Tohit

I certify that a Thesis Examination Committee has met on 11 July 2018 to conduct the final examination of Khairul Nizam Md Tohit on his thesis entitled "Development of Hybrid Problem Solving Method for Subsea Industry" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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The thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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I hereby confirm that:

- this thesis is my original work
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- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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Signature: ______________________________
Name of Member of Supervisory Committee: ______________________________

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LIST OF ABBREVIATIONS

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
ASMT	American Society of Medical Technologists
ASTM	American Section of the International Association for Testing Materials
CITV	Chemical Injection Tree Valve
CP	Cathodic Protection
CRA	Corrosion Resistance Alloy
DEMATEL	Decision Making Trial and Evaluation Laboratory
DHPT	Down Hole Pressure and Temperature Transducers
DHSV	Downhole Safety Valve
DNV	Det Norske Veritas As
EDX	Energy Dispersive X-Ray
FMEA	Failure Mode and Effect Analysis
FPSO	Floating Production Storage and Offloading
FSO	Floating Storage Offloading Vessel
HE	Hydrogen Embrittlement
HISC	Hydrogen Induced Stress Cracking
HISCC	Hydrogen Embrittlement and Stress Corrosion Cracking
HRC	Rockwell Hardness Measurement
ISO	International Organization for Standardization
IPA	Importance Performance Analysis
LAS	Low Alloy Steel
MCCR	Mechanical Completion and Checklist Reference
MITV	Methanol Injection Tree Valve
NORSOK	Norsk Sokkels Konkuranseposisjon
PPM	Pre-Production Meeting
PWB	Production Wing Block
RCA	Root Cause Analysis
SCC	Stress Corrosion Cracking
SLS	Subsea Lifecycle Services
XMT	Subsea Tree

CHAPTER 1

INTRODUCTION

1.1 Prologue

Subsea production system is representing a few combinations of facilities namely wellhead system, controls, subsea trees, manifolds and structures. It is known that the subsea operation involves many challenges such as high pressure containment, flow assurance in hostile sea surface and very low temperature. It is understood that the low temperature and high pressure are the common factors that may lead to high cost of repairs and maintenance (Cheliyan & Bhattacharyya, 2017). Subsea oil production system is spread in large geographical area that may cause the task of risk assessment for oil and gas leakage will become a highly extensive task. It is understood that the most powerful risk analysis method applied in the subsea industry is the fault tree analysis (FTA). This method uses a quantitative method for the computation of failure probability of each component in the particular system (Cheliyan & Bhattacharyya, 2017).

The failure probabilities of the basic events (*BE*) are the exact values as recommended in the conventional FTA. This is because precise estimation of failure probabilities for basic events is not practical. There is insufficient data recorded that prohibits the analysis to be performed (Liang et al., 2003). Therefore, it is often to perform the analysis with approximate probabilities of estimation in the absence of precise data. This is related to the usage of "possibility" instead of "probability" to complete the analysis (K.B. Misra et al., 2003).

There are various aspects of safety and reliability of subsea components that require special attention including review on the reliability estimates of the safety instrumented systems (Hui et al., 2012) and reliability of subsea trees (Wanvik et al., 1981). However, for subsea industry, the application of risk based methodologies especially the usage of FTA application is very rare (Cheliyan & Bhattacharyya, 2017). This contradicts with the aerospace and nuclear industries whereby the application of risk based methodologies have been well adopted (Cheliyan & Bhattacharyya, 2017).

Due to the nature of subsea production system which is complex, severe environment and inaccessible that are causing the operation, repair and maintenance are costly and time consuming. Thus, it is important that the quantitative risk estimation methodologies shall be adopted into subsea design and operation. A previous analysis made by Hu et al., (2012) analyzed the problem of leakage of oil and gas in a subsea production system. However, the analysis was considered sketchy and considered as a preliminary analysis. In comparison, there has been practically no work performed in the quantitative risk analysis (QRA) except for the preliminary study performed by Hu et al., (2012).

There is a challenge experienced for the fasteners used for critical applications in subsea industry. The challenges are in terms of selection of material, quality assurance and control, traceability's documentation for manufacturing, and production. Those challenges are crucial for meeting sufficient performance, components' integrity to prevent any costly failures. Criticality of subsea fasteners are defined as fasteners applied for pressure containing and primary load bearing joints. In addition, it also considers fasteners that are applied for joints or connections that have the potential of impacting the valves' functionality, safety, reliability and effective operational cost (Kirkemo, 2014).

Hydrogen induced stress cracking (HISC) or hydrogen embrittlement (HE) was identified as the major failure experienced during the last decade in the subsea industry. HISC primarily results from the hydrogen charging conditions of the cathodic protection (CP) system. A majority of fasteners use subsea from low alloyed steel grade type such as ASTM 320 Grade L7, L7M, L43 bolts with ASTM 194 Grade 4, 7M, 7 nuts. Those fasteners rely on the electrical continuity to the cathodic protection system. This is to prevent from sea water corrosion on the subsea trees that can potentially become the main contributor for HISC/HE. This may happen if the fasteners' hardness and strength level exceed the maximum ranges specified by the mill manufacturer (Kirkemo, 2014).

Cold formed hardened corrosion resistance alloy (CRA) is usually designated to be used if higher strength materials are required by engineering or design. There are a few grades used for this application such as grades 59, 660, 625, 686, 718, 725. However, the potential or probability of having HISC/HE depends on the hardness, strength range and manufacturing application. Majority of fasteners are used in the automotive and aerospace industries. For oil and gas industry, bolted connections are normally used for high integrity systems, high pressure containing connections and required a long-term performance like a structural components, pressurized vessels and piping (Pires et al., 2011).

It has become highly important for all bolted connections to be designed, manufactured and installed to the specified requirements to ensure long life cycle and reliability for various exposure and service conditions applied upon installation and application in subsea industry. The number of bolting failures may be due to various reasons namely overload, fatigue or corrosion. A few steps are taken seriously starting from the material selection, bolt manufacturing, coating and painting application like xylan and molykote application up to the final bolt installation process to ensure the bolt's functionality meets the desired design requirements.

1.2 Background

Subsea field in this study covers approximately 230 km offshore with the water depth range between 1200 m to 1400 m. The subsea production and injection system consists of several subsea stations namely production manifold, service umbilical, subsea trees, well jumpers with flowlines and umbilical connection to the Floating Production Storage and Offloading (FPSO) station as process facility as indicated in Figure 1.1. The production wells are clustered around the manifolds, with each manifold supporting each other.

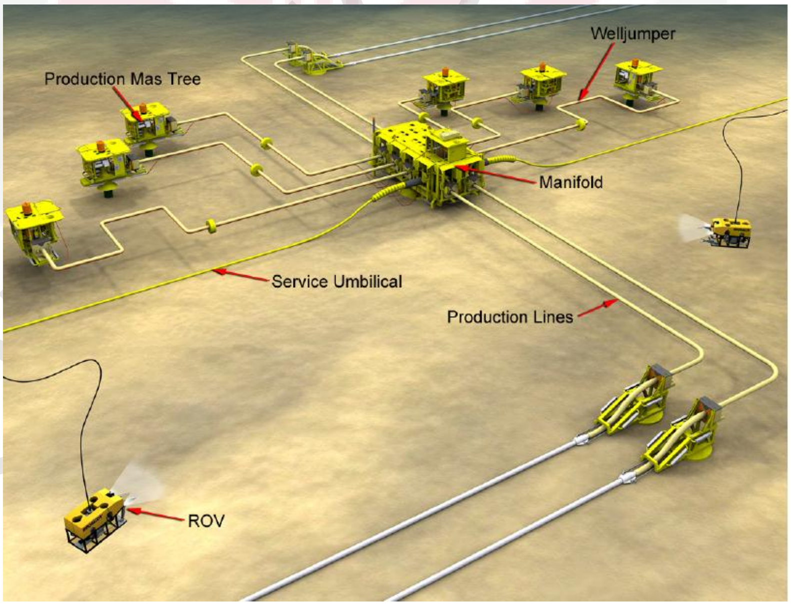

Figure 1.1: Subsea Production System (XMT Assembly)

The subsea station is defined to include the following systems:

1. Wellhead System
2. Subsea Trees (XMT) System including the work-over system
3. Subsea Production Control System including topside equipment
4. Tie-in System
5. Structures (including manifolds)

1.3 Subsea Trees

Subsea wellheads and Xmas trees are one of the important equipment in a subsea production system. The functions of subsea wellhead system performance will be similar with the same general functions of conventional surface wellhead. In general, a subsea Xmas tree is basically a combination of valves that are installed on subsea wellhead to ensure controllable interface between the subsea well and other production facilities. Different names for subsea trees are Christmas tree, cross tree, X-tree or tree (Yong Bai et al., 2012).

Different subsea trees will be used for different applications such as production of water/gas injection. Subsea wellhead systems are normally designed according to the standard and codes as below:

1. API 6A, Specification for Wellhead and Christmas Trees Equipment;
2. API 17D, Specification for Subsea Wellhead and Christmas Tree Equipment;
3. API RP 17A, Recommended Practice for Design and Operation of Subsea Production Systems;
4. API RP 17H, Remotely Operated Vehicle (ROV) Interfaces on Subsea Production System;
5. API RP 17G, Design and Operation of Completion/Workover Risers;
6. ASME B31.3, Process Piping;
7. AWSD 1.3, Structural Steel Welding Code;
8. DNV RP B 401, Cathodic Protection

The subsea trees' functions and requirements should be referred as below:

i. To provide orientation of the wellhead and tree system with respect to the tree-to-manifold connection (Yong Bai et al., 2012)
ii. To interface with and support Xmas tree system and blowout preventer (BOP) (Yong Bai et al., 2012)
iii. To ensure alignment, concentricity and verticality of the low-pressure conductor housing and high pressure of wellhead housing (Yong Bai et al., 2012)
iv. To prove the field design that is able to serve with minimum sensitivity to water depth and sea conditions (Yong Bai et al., 2012)

Figures 1.2 and 1.3 show the physical condition of the Subsea Tree with Methanol Injection Tree Valve (MITV) and Chemical Injection Tree Valve (CITV) positions. The valves are mounted on the lateral sides that allow simple well intervention and tubing recovery. This will be an added advantage for wells that require a high number of interventions (Yong Bai et al., 2012).

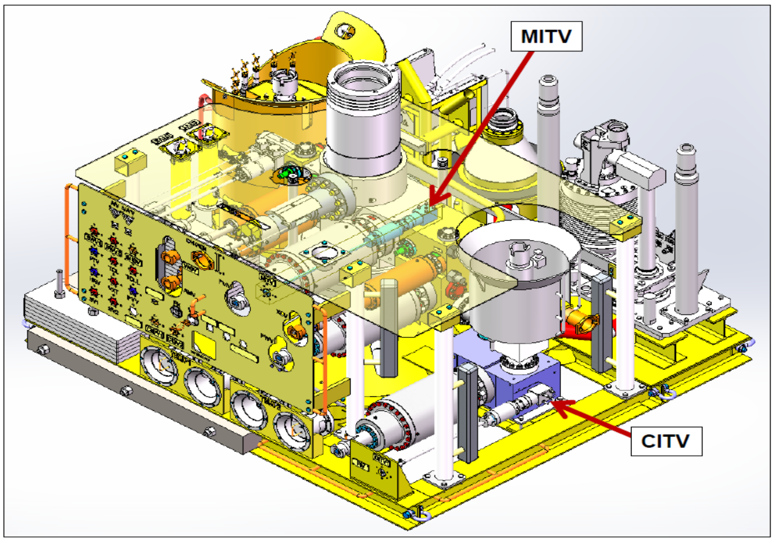

Figure 1.2: Subsea Tree with MITV and CITV positions (XMT Assembly)

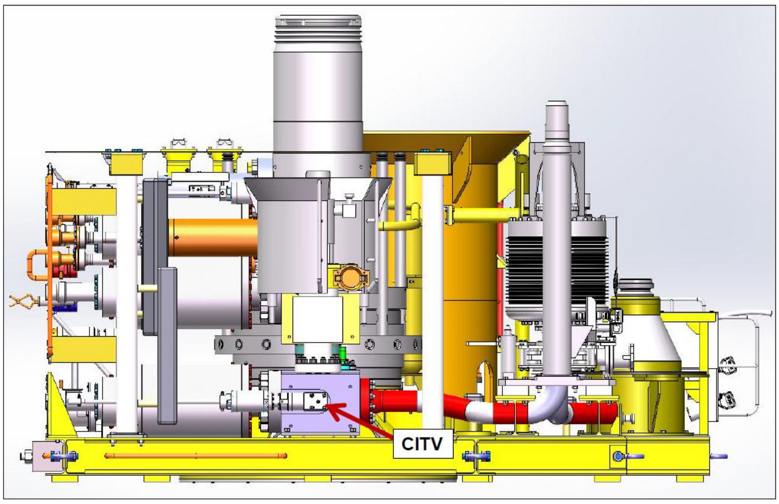

Figure 1.3: Subsea tree with CITV Position (XMT Assembly)

1.4 Problem Statement

One of the prominent 21st century skills is the ability to solve complex problems that represent the actual life situation. This skill requires interaction with unknown environment (Greiff et al., 2013; Molnár, Greiff, & Csapó, 2013). Real-life situations also represent a static problems that can be resolved with the assistance of reasoning and connecting the provided information with the problem (Scherer & Tiemann, 2014). Decision process is related to the set of actions and methods that are dynamically organized (Castro & Parreiras, 2018). The process will start from a request for action and will be completed with a specific agreement of execution process. The organization has to choose the best option of averaging the outcomes from each different stakeholder for finalizing the decision (Firouzabadi et al., 2008).

The decision-making problem is considered as hard and challenging due to these reasons:

1. They are non-repetitive, unprecedented and unique (Firouzabadi et al., 2008)
2. Criteria may conflict within themselves. For example, customers want to have high quality products but not expensive (Bai et al., 2015) (Tseng et al., 2007)
3. Tangible vs intangible criteria. For example, tangible criteria consist of objectively be measured like a fuel consumption. For intangible criteria, the examples are like the flexibility, quality, and efficiency. This cannot be converted into a numeric value (Yang et al., 2006) (Ordoobadi et al., 2001)

Multiple-criteria decision making (MCDM) is a combination of methodologies to perform a comparison, selection and establishing a ranking system where multiple and various conflicting criteria are involved consisting of tangible and intangible criteria (Castro & Parreiras, 2018). MCDM has been widely used in resolving the real decision making problems. The application of MCDM technique is inclusive from the autonomous drive until the assessment of Mars mission (Chen et al., 2014). On the other hand, the MCDM technique has also been widely used for supplier selection, evaluation and material selection (Castro & Parreiras, 2018).

MCDM techniques have been successfully applied to a wide range of applications in automotive industry with engineering design heavily relying on this technique for problem solving analysis and decision making analysis. The Analytical Hierarchy Process (AHP) is the most consistent technique followed by PROMETHEE as integrated approaches are more usual than individual ones. There are numbers of application of fuzzy methods to tackle uncertainty observed being applied for this application (Castro & Parreiras, 2018). It is known that MCDM method is suitable for dealing with the complex decision-making in automotive sectors with different subjects and terms but no further analysis is performed for EE scope. There's a gap identified in the automotive industry.

The integration of three research methods known as FMEA-IPA-DEMATEL analysis model is being used in the semi-conductor industry. FMEA is pragmatic to detect the features to be enhanced, followed by employing IPA to deliberate the enhancement of the significance and performance of the features. Finally, DEMATEL is used to discover the underlying relation and interface among those features. The objective of performing this analysis is to help the decision-makers to ascertain the essential difficulties to be enhanced and give proposals on the problem-solving structure (Tsai et al., 2018). FMEA is commonly used during the beginning of design stage that actively involves participation from various groups of people from different departments especially from Engineering and Manufacturing. This application is not really suitable to identify the actual cause of failures while dealing with the real-field issues that require prompt actions to be taken in terms of containment, correction, corrective and preventive actions.

Hybrid problem solving technique will be used as part of the integration techniques that combined two methods of the root cause analysis technique consisting of Cause and Effect diagram with the 5 Whys analysis techniques. This technique is arranged in sequence in A3 analysis template to assist the decision-makers and respective stakeholders to evaluate the problems, perform analysis, and establish the final mitigation actions such as containment and permanent solutions to ensure no re-occurrence for similar issues in the future. The validation of case study by using this method will be performed to ensure the effectiveness of the newly suggested method compared to various problem solving method technique and not limited to the subsea industry alone.

1.5 Objectives of Study

The purpose of this study is to review the application and implementation of hybrid problem solving method to identify the actual cause of failures in subsea industry. This study aims to address the following:

1. To analyses current problem solving methods applied for different industries
2. To develop hybrid problem solving method that preventing failures in subsea industry

3. To validate hybrid problem solving method by using case study in subsea industry

1.6 Scope of Work

In this study, development of A3 analysis method by performing the hybrid method from cause and effect diagram (fishbone diagram) and 5 Whys analysis technique are chosen to be used to identify the actual cause of failure. Upon identifying the actual cause of failure, corrective and preventive actions measured are taken to minimize the effect of failure and to come out with the recommendation actions on how to improve the situation for future products.

The failure for this incident is considered as re-occurrence and the subject of the failure may contribute to the fastener's material selection decision. Thus, proposed lab analysis based on the new stud bolt material for the same application that will be used for future design of subsea tree will be tested with controlled parameter of subsea environment. The objective is to understand the mechanical behavior and reaction towards the subsea environment and to confirm if there are any differences on the chemical composition compared to the failed stud bolt.

1.7 Limitation of Works

Literature review on the different methodologies on problem solving methods is limited to the literature search performed between year 2010 to 2018. This is to ensure only recent problem solving methods applied for different industries are still reliable to compare with. The proposed improvement material that will be used for future subsea tree's design was tested based on the guideline and reference made to ASTM D1141 Artificial Seawater. The analysis was performed by comparing the test analysis results for the failed stud bolt versus the fresh stud bolt from the same batch. The input from mill supplier in regards of the manufacturing process control was not able to be obtained due to expiration of the documentation record of more than 7 years.

The identification of actual cause of failure will heavily rely on the final output from the 5 Whys analysis technique. Further analysis may be required to continue with the whys upon having the information from the mill suppliers.

This is important to understand on how the material hardness was controlled and reviewed during in-process stage.

1.8 Thesis Layout

The present thesis consists of five chapters namely the introduction, literature review, methodology, results and discussion, and conclusion and recommendation. The first chapter - introduction provides a general information and background of subsea industry in terms of equipment used and the process involved. Problem statement, objective of study, and scope of work are also discussed and presented to ensure proper flow is shared to create some awareness and interaction with readers.

Chapter two - literature review discusses and overviews previous similar study conducted earlier in terms of overall quality management, quality tools and techniques, and decision making methodology used to resolve the issue. The literature review continues with detailed review on similar incidents happening in the past during the subsea operation of the usage of the similar fasteners during operation and understand the cause of failures and corrective actions taken to improve the situation. Finally, findings of literature review are compared against each other to establish the research gap to come out with the proposal to improve the project.

Chapter three - methodology describes the process flow on how to achieve the objective of study. This chapter is focusing on the application of quality tools and techniques to detect the real cause of failure and establish the recommended actions for improvements. Proposed lab analysis consists of suitable jig design, code and practice, and standard of operation which was formed to provide guidance and reference during the actual testing activity.

Chapter four - results and discussion discuss the results from the A3 analysis technique with supporting data from the lab analysis report. Results of the lab analysis will be used to establish the empirical data such as mechanical properties, hardness value and chemical composition that will be used to conclude the findings on the analysis.

Chapter five - conclusion and recommendations emerge the conclusions based on the objectives of investigations and problem analysis of the study and recommendation for future studies.

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